Report of the Astromag Definition Team

THE PARTICLE ASTROPHYSICS MAGNET FACILITY

ASTROMAG

May 1988

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I: INTRODUCTION

Particle astrophysics stands today at a critical juncture in its development. Observations over the past several years have given unexpected results on the elemental and isotopic composition of cosmic-ray nuclei and on the cosmic-ray abundances of antiprotons and positrons. Concurrently, theoretical developments have presented us with a new framework in which to understand the acceleration of these particles. These results have raised new questions about the origins of energetic particles in astrophysical settings, sometimes deeply related to fundamental questions of astrophysics, cosmology and elementary particle physics. For example: What is the source of the large abundances of antiprotons observed in the cosmic radiation? Is there evidence for known or unknown particles which could account for missing mass in the universe? What is the nucleosynthetic history of this sample of non-solar system material? Answering these questions requires long space exposures of large instruments; the development of a permanently manned Space Station offers the opportunity to perform the needed experiments.

Over the past 3 years the Particle Astrophysics Magnet Facility (Astromag) Definition Team has examined how a large magnetic spectrometer outside the Earth's atmosphere for an extended period of time could address these questions. A facility, composed of a core magnet, dewar, and associated support equipment would be used to conduct a series of experiments using a variety of instrumentation. A number of magnet and instrument configurations have been considered, and it appears to be quite feasible to construct and operate such a spectrometer facility on the Space Station. In this report, the scientific objectives that could be addressed by this facility are summarized and a "strawman" configuration of magnet and instruments capable of achieving some of those objectives is described. The remaining objectives would be achieved by changing and reconfiguring the instrument complement used in conjunction with the magnet. Plans for management and for technical development of the Astromag facility are outlined.

Most of the scientific objectives for Astromag require the long, on-orbit exposures possible on the Space Station, and most objectives can be met in its 28-degree orbit. On the other hand, some limited but important objectives not attainable in a low inclination orbit could be met with 1-week exposures in a Shuttle-attached mode in high-inclination (> 50-degree) orbit. If the Space Station were to be delayed significantly, an appropriate configuration of instruments could be flown with the magnet on a high-inclination Shuttle mission prior to placing Astromag on the Space Station.

SUMMARY OF SCIENTIFIC OBJECTIVES

The primary scientific objectives of Astromag are to:

- o Examine cosmological models by searching for antimatter and dark matter candidates.
- o Study the origin and evolution of matter in the galaxy by direct sampling of galactic material.
- o Study the origin and acceleration of the relativistic particle plasma in the galaxy and its effects on the dynamics and evolution of the galaxy.

These general scientific objectives will be met by Astromag with particle detection instruments designed to make the following observations:

- Search, with unprecedented sensitivity, for anti-nuclei of helium and heavier elements--The identification of any such anti-nuclei would imply that the Universe contains domains of antimatter and would have profound cosmological implications.

- Measure the spectra of anti-protons and positrons--These anti-particles have already been seen in the cosmic rays, and they are expected as secondary products of primary cosmic-ray interactions with the interstellar gas; however, antiproton fluxes are higher than expected from normal models of galactic cosmic-ray propagation. Further investigation of these spectra will surely improve our understanding of the origin of cosmic rays and may lead to the discovery of processes unpredictable from present knowledge of elementary particle physics and cosmology.

- Measure the isotopic composition of cosmic-ray nuclei at energies of several GeV/amu (higher than reached by other means) and with previously unattained sensitivity--The few reliably measured elements show that the isotopic composition at the cosmic-ray source is different from that of ambient material found in our solar system. Distinguishing among models of cosmic-ray sources which might explain these differences requires isotopic composition measurements of many other elements at different energies and with much greater sensitivity than presently achieved. In addition, measurement of radioactive isotopes over a range of Lorentz factors will answer questions about the storage of cosmic rays in the galaxy.

- Measure the energy spectrum of cosmic ray nuclei to very high energies with unprecedented precision--Spectral differences between primary and secondary nuclei are indicative of galactic confinement processes and can lead to the determination of source abundances of rare elements. Fine structure in the energy spectra, if observed, would revolutionize ideas about the origin of cosmic rays.

These and other objectives are described in more detail in Section II of this report.

GENERAL STRUCTURE OF ASTROMAG

The Astromag design is based on the following principles of particle detection. An incoming particle is deflected as it passes through a very strong magnetic field produced by superconducting currents in a system of coils (the magnet). The sign and magnitude of the deflection are measured by high precision particle tracking detectors. Triggering detectors above and below the magnetic field provide information for identifying the particle and define an acceptance solid angle for the particle "telescope". They determine not only the magnitude of its electric charge but also the direction of travel of the particles, and they provide indication to the instrument electronics of the passage of an event to be analyzed. Typical particle trajectories are shown schematically in Figure I-1.

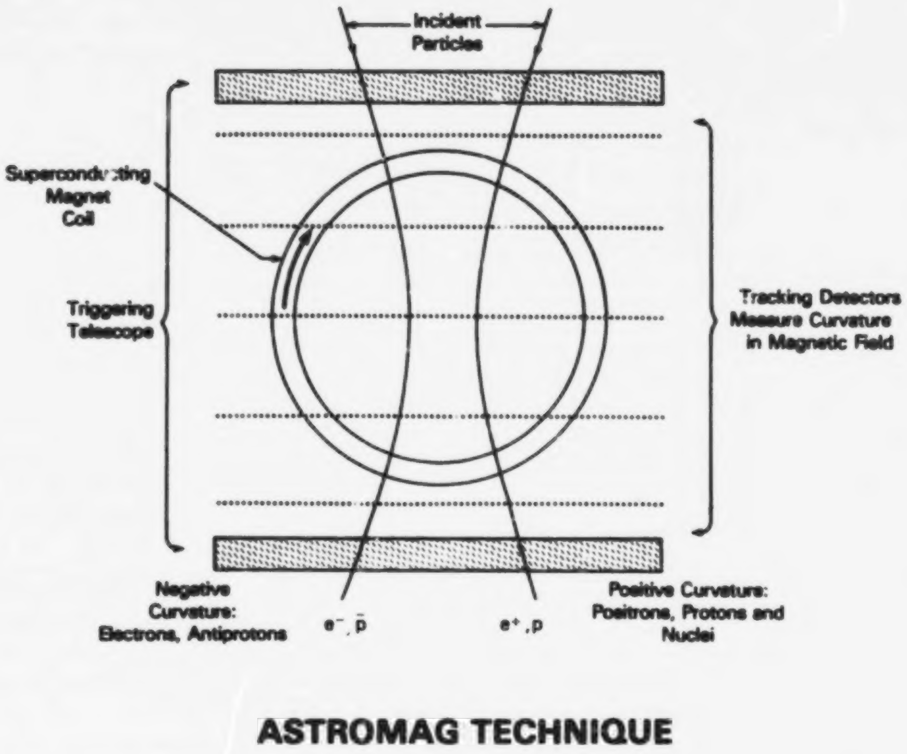
Incident Particles
Superconducting Magnet Coil
Triggering Telescope
Tracking Detectors Measure Curvature in Magnetic Field
Negative Curvature: Electrons, Antiprotons
$e^-, \bar{p}$
e^+, p
Positive Curvature: Positrons, Protons and Nuclei
ASTROMAG TECHNIQUE

Figure I-1: **Astromag Technique.** The superconducting coil creates a strong magnetic field which deflects the trajectories of the highly relativistic incident particles. The direction and magnitude of curvature through the magnetic field are measured by particle tracking detectors.

To undertake the variety of observations listed above, at least two different detector configurations will be required; one for protons, electrons, and the other low-charge particles and another for higher charged nuclei. As a result, the instrumentation for the Astromag will be mounted in two separate sections, as shown in Figure I-2. These two sections are likely to have different trajectory defining detectors, one set optimized for lower charged particles and the other for higher charges. The two sections will have different complements of triggering detectors optimized for the particular measurements being made in each section. This logical subdivision, dictated by the technical requirements for the different measurements, is independent of the details of the coil configuration in the magnet.

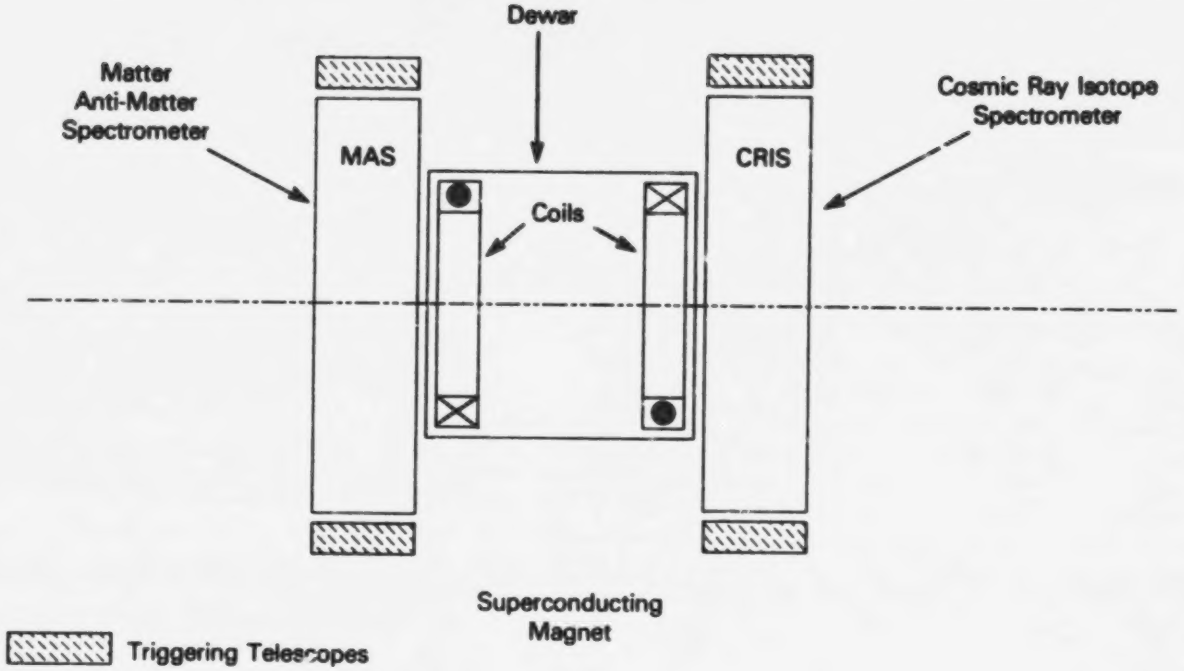
Dewar
Matter Anti-Matter Spectrometer
MAS
Coils
CRIS
Cosmic Ray Isotope Spectrometer
Superconducting Magnet
▨ Triggering Telescopes

Figure I-2: **Schematic of Astromag.** The current in the two superconducting coils circulates in the opposite sense, leaving the magnet with no net dipole moment. The dewar containing liquid helium is located between the two coils. Two experiments can be operated simultaneously, one on each end of the magnet.

THE MAGNET SPECTROMETER

The heart of the Astromag system is the superconducting magnet. A variety of coil configurations have been considered. The final choice will be based on studies of performance, cost and safety trade-offs to be performed during 1986 and 1987. The "strawman" facility described in this report uses a coil configuration similar to that designed for the HEAO program in the early '70's, scaled up to meet present requirements. A prototype magnet was built and tested as part of that program and has provided a base of experience. In general, a magnet which will satisfy our scientific requirements can be built using currently available technology. (The actual value depends on the minimum magnetic rigidity resolution sought).

This magnet configuration, shown in Figure I-3, consists of two circular coils, each about 1.3 m in diameter and separated by 2 m, inside a single cylindrical dewar. Currents in the two coils have opposing senses, so the overall system has no net dipole moment and thus does not exert any significant torques on the Space Station. This configuration provides two prime locations for instrumentation, just outside each coil. At each end there is

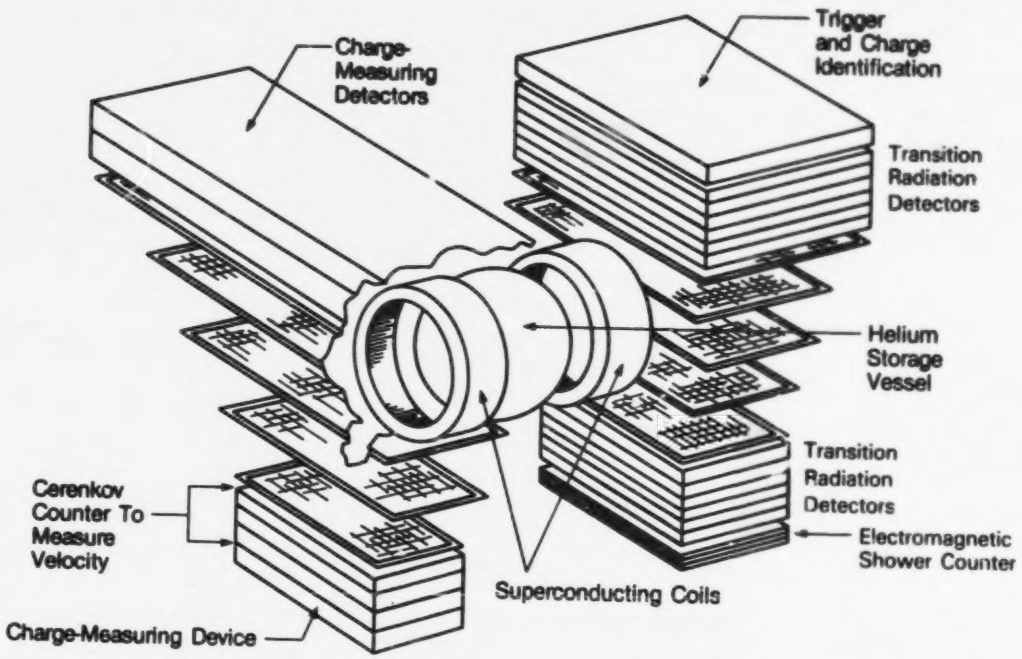
PARTICLE ASTROPHYSICS MAGNET SPECTROMETER
Charge-Measuring Detectors
Trigger and Charge Identification
Transition Radiation Detectors
Helium Storage Vessel
Transition Radiation Detectors
Electromagnetic Shower Counter
Cerenkov Counter To Measure Velocity
Superconducting Coils
Charge-Measuring Device

Figure I-3: Particle Astrophysics Magnet Spectrometer

sufficient volume of high magnetic field to accommodate a detector system with geometry factor of about 0.1 m^2sr.

The superconducting magnet requires liquid helium to keep the coils in the superconducting state. In order to make Astromag a long-term facility, periodic helium resupply will be necessary. Resupply is assumed to take place every 18 to 24 months assuming a cryostat designed to hold sufficient helium for 30 months. Mounting this facility on the Space Station, where a manned presence and frequent visits by the Shuttle are planned, will facilitate this periodic resupply.

Safety considerations for superconducting magnets are now well understood, as a result of their widespread use in terrestrial laboratories. The system will be designed to withstand without damage the sudden collapse of the magnetic field and the dissipation of that energy. This contingency would occur if the liquid helium were suddenly lost or if for any other reason the conductor made the transition from the superconducting state to the normal state.

The basic magnet facility measures the magnetic rigidity, R, (momentum per unit charge) of charged particles. The precision of this measurement is characterized by the maximum detectable rigidity (R_{max}) which depends directly on the field integral (the integral of the magnetic field strength over the trajectory of the particle) and inversely on the positional error of the track measuring devices. With the field integral of the "strawman" magnet and position detectors with 50 μm resolutions, instruments can be placed at each end of the magnet with geometry factors of 0.1 m^2sr for R_{max} greater than 2 TV.

Candidates for the high and low charge trajectory measuring detectors are, respectively, Multiwire Proportional Counters (MWPC) and Scintillating Optical Fiber Trajectory (SOFT) detectors. Each can achieve resolution in the range of 50 μm, while introducing such small amounts of material into the particle path that the resolution is not degraded by multiple Coulomb scattering of the particle. MWPC's have been successfully used with magnetic spectrometers for singly charged particles, and SOFT detectors have achieved this resolution in the laboratory with iron nuclei.

The magnet and trajectory detectors are discussed more fully in Section III of this report.

INSTRUMENT CONFIGURATION

An instrument configuration capable of making the desired observations with the required precision is feasible with modest extensions of flight-proven detector systems. An Astromag which initially carries an instrument complement similar to the configuration defined here and which would be periodically modified by exchanging detector systems is envisioned. The two instruments are indicated in Figures I-2 and I-3.

At one end is a Matter-Antimatter Spectrometer (MAS). This set of instruments is optimized for measurements of protons, antiprotons, electrons, and positrons over an energy range from a few GeV to about a TeV. It will also be suitable for measurement of energy spectra of elements with atomic number up to about 10 at energies from a few GeV/amu to a few hundred GeV/amu, and for high-resolution measurement of gamma rays with energy between about 1 and 100 GeV. It will also be suitable for high sensitivity searches for antinuclei with atomic number 2 to 10 at energies above a few GeV/amu. In addition to the basic magnetic spectrometer, MAS uses scintillation counters, transition radiation detectors and an electron shower counter to distinguish among the various species of incident particles. It has a geometry factor of about 0.1 m^2sr for R_{max} of greater than 2 TV.

At the other end is a Cosmic Ray Isotope Spectrometer (CRIS). CRIS is optimized for measurement of the isotopic composition of elements with atomic number 6 to 28 at energies of several GeV/amu. It will also be suitable over the same range of atomic numbers for measurement of elemental composition from a few to a few hundred GeV/amu and for searches for antinuclei at energies above a few GeV/amu. In addition to the basic magnetic spectrometer, CRIS uses Cherenkov counters of various indices of refraction to measure the charge and velocity of the incident particles. It has a geometry factor greater than 0.1 m^2sr for R_{max} of greater than 2 TV.

Section IV of this report describes these detector systems and their capabilities in more detail. Additional detector systems which would be appropriate for later development and for replacing the original instrumentation are also described.

INTERFACES WITH THE SPACE STATION

Astromag is well suited for installation on the Space Station early in its operation. It makes few demands on the Station while requiring its unique capabilities for servicing and reconfiguring experiments. The Space Station naturally provides orientation so the instruments look away from earth. Aspect information will be required post facto. The instruments are not sensitive to contamination from other activities on the Station, and they should not cause contamination, since Astromag vents only helium and, possibly, small quantities of proportional counter gas.

There is a substantial fringe magnetic field close to the magnet, but since there is no net dipole moment, the magnet does not exert a torque on the Station and the magnetic field falls off rapidly. At the edge of the Astromag detectors, about 2 meters from the coils, the magnetic induction would be less than 1000 Gauss (0.1 Tesla). The field falls to 25 Gauss between 5 and 6 m from the coils and falls below 1 Gauss between 11 and 13 m.

The system will require resupply of liquid helium about every 18 to 24 months, and there will be periodic (year or two intervals) changeout of instrumentation. Thus this facility takes advantage of some of the unique capabilities offered by the Space Station, without unduly taxing those capabilities.

Section V of this report describes the interfaces with the Station and the on-orbit operations in more detail. That section also describes interfaces with the Shuttle.

MANAGEMENT AND DEVELOPMENT PLAN

Goddard Space Flight Center, as the designated development Center, will be responsible for the overall management of the project. The Space Science and Applications Directorate will provide a Project Scientist and institutional science support. Other Goddard Directorates will support the development as needed.

The core of the Astromag facility includes the superconducting magnet with associated dewar and its control and charging devices, the support structure, the central data systems, power and telemetry subsystems, and all supporting equipment. This core will be procured by Goddard Space Flight Center. The Study Team suggests that the core be developed in close consultation with a Facility Integration Science Team (FIST).

The instrumentation for each experiment, including trajectory detectors, will be developed by an experiment team selected by an Announcement of Opportunity (AO). The FIST would be appointed by NASA from among individuals who apply in response to the AO. A Science Working Group (SWG) would coordinate efforts of the various groups.

To encourage wide participation, including participation by theoreticians and by experimenters who are not in a position to develop major hardware, a class of General Investigators assigned as appropriate to the experiment teams and to the Science Working Group is suggested.

This management plan is elaborated in Section VI.

The Astromag development schedule on which this report is based assumes Space Station availability in 1994. The detailed magnet and instrument development schedule activities identified during the Astromag study phase are discussed in detail in Section VII.

II. SCIENTIFIC OBJECTIVES

The proposed Astromag facility will be capable of measuring with unprecedented accuracy the spectra of high energy electrons, positrons, protons, antiprotons, and nuclear isotopes that orginate in our galaxy and possibly beyond, as well as performing sensitive searches for more exotic forms of high-energy matter. By analyzing in detail the products of astrophysical processes that result in highly relativistic particles, Astromag will address a wide range of fundamental questions, complementing observations made by the great electromagnetic observatories, ST, GRO, AXAF, and SIRTF, and by ground-based and other studies. An overview of the objectives described in this report is presented below.

A. OVERVIEW

1. **Antimatter in the Universe** - The question of the degree to which the universe contains antimatter is fundamental to cosmology. Accurate measurements of the high-energy spectra of cosmic ray nuclei, antiprotons, electrons, and positrons will help answer this question by allowing Astromag to:

- o Search for anti-nuclei of either galactic or extragalactic origin with a sensitivity that is improved beyond present limits by orders of magnitude.
- o Search for the origin of the overabundance of anti-protons observed in cosmic rays.
- o Examine the spectra of anti-protons and positrons for the signatures of exotic processes such as photino annihilation, the decay of primordial black holes, or contributions from anti-galaxies.
- o Study anti-proton and positron production in nuclear interactions taking place in cosmic ray sources and in the interstellar medium.

2. **The Origin and Evolution of Galactic Matter** - Cosmic rays represent a directly accessible sample of matter from outside the solar system. Elemental and isotopic composition studies at high energies will make it possible to:

- o Examine a sample of galactic matter for evidence of nucleosynthesis and galactic evolutionary effects that distinguish it from solar system matter.
- o Measure the time delay between nucleosynthesis and cosmic ray acceleration using K-capture radioactive "clocks".
- o Search for evidence of special sources of cosmic rays such as supernovae or Wolf-Rayet stars.
- o Extend high-precision studies of the elemental composition of cosmic rays to very high energies.

3. The Acceleration and Propagation of Energetic Particles in the Galaxy
High energy particles play a major role in the dynamics of the galaxy. Thus, for example, the energy density of cosmic rays is comparable to that of the galactic magnetic field and to that of gas motion. The combined spectral and composition observations of high-energy cosmic-ray nuclei and electrons will make it possible to:

- Determine the containment time of various cosmic ray species in the galaxy, by measuring radioactive "clock" nuclei over a range of time-dilation factors.
- Determine the density and distribution of matter traversed by cosmic rays through observations of secondary particles such as antiprotons, positrons, ^2H, ^3He, and the rare elements Li, Be, and B.
- Search for evidence of cosmic ray acceleration by interstellar shock-waves.
- Search for individual, nearby sources of cosmic ray electrons with TeV energies.

The objectives above can be accomplished using state-of-the-art instrumentation. It is expected that major steps in addressing most of these goals would be taken by the first generation of Astromag experiments, and "strawman" instrumentation to accomplish this is described in Section IV.

A variety of other objectives could be accomplished with second generation experiments, including experiments located in the fringe field of the magnet. For example, a large area, high angular resolution γ-ray survey experiment could be built to localize sources of 1 to 100 GeV γ-rays with sub arc minute precision and to search for sources with hard sources characteristic of shock acceleration. The detailed focus for such an experiment would of course depend on the outcome of studies with the Energetic Gamma Ray Experiment Telescope to be flown on the Gamma Ray Observatory around 1990. Additionally, some unique plasma physics experiments are possible as are studies of some solar and heliospheric phenomena.

Astromag could also provide the opportunity to search for a variety of exotic particles, predicted by elementary particle theory, which might be produced in astrophysical settings, for instance, narrow γ-ray line paris have been predicted as a result of the annihilation of photinos or other massive Fermions. Such experiments could set new limits on fundamental processes that may take place in the universe.

B. PRIMARY OBJECTIVES

The unique capabilities of a large magnet spectrometer in space provide the opportunity for high-resolution particle spectroscopy over a significant portion of the cosmic ray energy interval from 1 GeV to 1000 GeV (or GeV/amu in the case of nuclei). This opportunity makes it possible to address a wide range of scientific objectives, including several at the forefront of particle astrophysics research that could not presently be addressed by other means. It is these primary objectives that provide the principal scientific justification for Astromag, that will drive the design of the magnet and the core facility, and that will in all probability guide the selection of the initial complement of experiments. Summaries of these primary objectives appear below.

1. Antiproton Studies

A fundamental question in cosmology and astrophysics is to what degree the universe exhibits matter/antimatter symmetry. For some time it has been realized that cosmic rays can shed light on this problem, since they represent a sample of matter from outside the solar system that may even contain contributions from extragalactic sources. It has, of course, been expected that cosmic rays would contain a measurable flux of "secondary" antiprotons (as well as positrons) produced in high-energy collisions of cosmic rays with the interstellar gas. At the same time more exotic sources of antiprotons have also been proposed that might add to and modify the spectrum of antiprotons in predictable ways. The goal of antiproton measurements on Astromag is the determination of their spectrum from 2 to 500 GeV with sufficient precision to differentiate among the various possible origins that may contribute to this flux.

Although cosmic ray antiprotons have proven to be elusive, within the past decade measurements of a finite flux were reported by three balloon-borne experiments. Figure II-1 displays the current status of measurements of the antiproton to proton ratio along with the predicted ratios for several cosmic ray propagation models. Note that the available measurements give an intensity at least three times greater than expected from secondary production in the standard "leaky box model" of cosmic ray propagation (curve labeled 7 g/cm^2), a model developed to fit the abundances of cosmic ray nuclei with $Z \leq 28$.

As a result of this disagreement, it has been suggested that cosmic ray protons (and perhaps also He) may have had a different origin and history from that of heavier nuclei. Figure II-1 shows the predictions of several models, all of which assume that antiprotons are of secondary origin. These models differ in the amount and location of the material traversed by cosmic ray protons. Thus, the curve labeled "21 g/cm^2" arbitrarily scales the proton pathlength distribution by a factor of 3, in order to match the high-energy antiproton data. Among the other proposed possibilities is the so-called "closed galaxy" model, in which there are two cosmic ray components, one of which is "old" and has traversed a great deal of material.

Another class of models proposes that a portion of cosmic rays originate in sources surrounded by a thick shell (e.g., about 50 g/cm^2) of matter, perhaps supernovae explosions in dense clouds. Such objects would also be high-energy γ-ray sources. The predicted slope of the high-energy antiproton spectrum from such models depends on the detailed assumptions of the model. For example, the slope is predicted to be proportional to $E^{-2.7}$ if antiprotons are further accelerated after production in the source (curve labeled "collisional injection" in Figure II-1). Unless there are mechanisms that significantly decelerate particles after their production in interstellar collisions, antiproton spectra resulting from high-energy interactions would be expected to exhibit a "kinematic cutoff" below a few GeV. Other secondaries such as positrons, deuterium, and ^{3}He will help to delineate the contribution that these interactions make to the observed antiprotons.

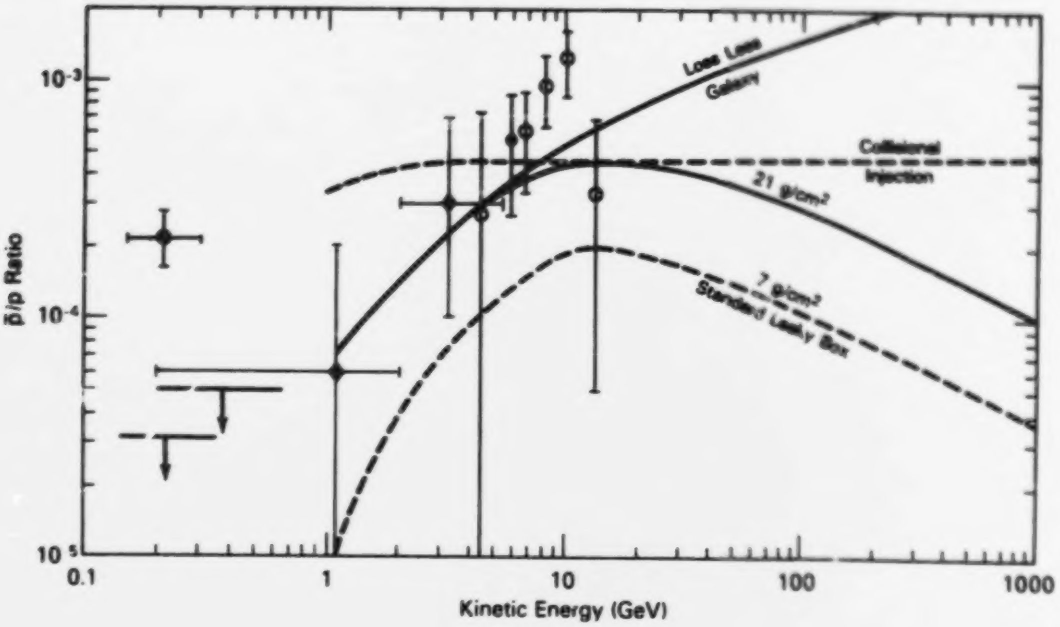

Figure II-1: A summary of measurements of the cosmic ray antiproton to proton ratio, compared with the predictions of several propagation models in which antiprotons are produced as interaction "secondaries", including the "standard leaky box" model (labeled 7 g/cm²) that fits heavier secondary nuclei.

Should the interaction models fail to match the observed characteristics of the antiproton spectrum, serious consideration will have to be given to more exotic proposals for producing antiprotons. These include the decay of primordial black holes left over from the big bang, and antiprotons originating in anti-galaxies. These two hypotheses would lead to distinctly different energy spectra above 20 GeV.

Finally, it has been suggested that the observed flux of cosmic ray antiprotons may result from the annihilation of generic higgsinos or Majorana neutrinos. These particles have been proposed as candidates for the invisible mass in the universe in theories that attempt to explain the very early Universe and to unify the four fundamental forces of nature. As indicated

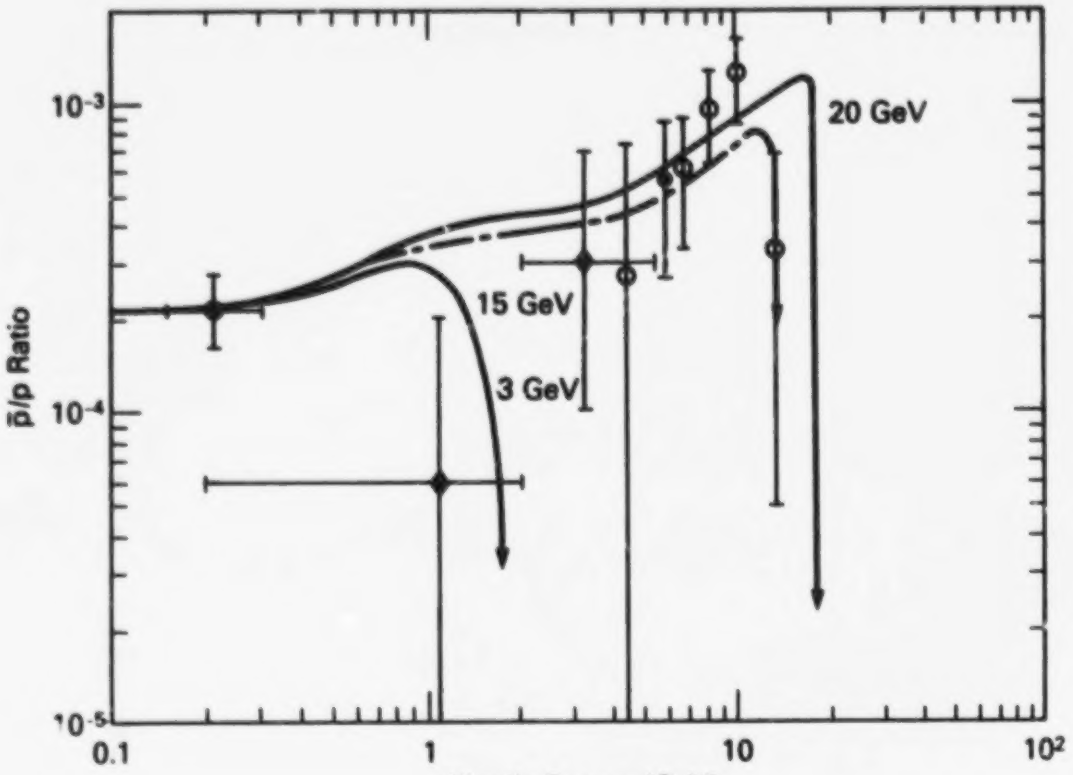

Figure II-2: Calculated antiproton to proton ratios resulting from photino annihilation in the galactic halo are compared with the available cosmic ray measurements, including the differential spectrum of the 4-12 GeV data in Figure II-1. Fits are shown for assumed photino masses of 3, 15, and 20 GeV.

in Figure II-2, dark matter candidate particles annihilate resulting in antiproton spectra that cut off at an energy corresponding to the particle mass. If more precise measurements show a sharp cutoff in the antiproton spectrum, it would be strong evidence for the existence of Majorana Fermions in the galaxy. Gamma-ray lines that might be observable by Astromag may also be a signature of these particles.

Over the next few years balloon experiments now under development will provide improved measurements of the antiproton spectrum below 10 GeV. These experiments should decide whether atmospheric contributions are significant in the balloon data. Recent measurements of low energy spectrum are shown as upper limits in Figure II-1 confirm the expected behavior. However, measurements in the 10 to 100 GeV energy range and beyond are required to distinguish between the various interaction-secondary models (Figure II-1), and to decide whether more exotic explanations are required.

In section IV.A. a possible Astromag experiment is described that could measure the antiproton spectrum from 4 to 500 GeV with a collecting power 1000 times that of the balloon experiments, with excellent energy resolution. Measurements of lower energy antiprotons that might be obtained on a high-latitude STS flight of Astromag are discussed in Section IV.C.

2. Cosmological Antimatter

Detection of heavy ($Z \geq 2$) antinuclei would be a discovery of fundamental significance because current cosmology suggests that such antimatter does not exist. Cosmic ray searches that have been made to date have yielded only upper limits of one part in 10^4 for heavy antinuclei ($Z>2$) and several parts in 10^5 for antihelium. Astromag should be able to extend the present sensitivity limits by several orders of magnitude.

Three conditions are necessary to generate a matter/antimatter asymmetry from an original Hot Big Bang: baryon-nonconservation, CP violation, and a non-equilibrium environment. The CP violation is seen in the laboratory, and the rapid expansion of the Universe following the Bang could easily generate the non-equilibrium environment. Further it is believed that most of the baryons produced in the Bang have in fact disappeared. Baryons and photons would be produced in the Big Bang in equal abundance but from observation of the 2.7K cosmic background radiation and the present matter density of the universe we know that only about one baryon remains for every billion photons. Because one part in 10^9 is close to the level of CP violation, the current theory suggests that the remaining matter is the remnant of the almost complete annihilation of matter and antimatter at some early epoch, which stopped only when there was no more antimatter to annihilate.

On the basis of gamma-ray observations and other considerations the coexistence of condensed matter and antimatter on scales smaller than that of clusters of galaxies has been virtually ruled out. However, no observations presently exclude the possibility that the domain size for establishing the sign of the CP violation is as large as a cluster or supercluster of galaxies. For example, there could be equality in the number of superclusters and anti-superclusters. Similarly, there is nothing which excludes the possibility that a small fraction of the cosmic rays observed at Earth reach our galaxy from nearby superclusters. No accurate quantitative assessment of the probabilities is available, however.

Observations of the diffuse gamma ray flux indicate that the relative abundance of antimatter in intergalactic space is probably less than 10^{-9} unless there are well separated domains of matter and antimatter. Astromag will be able to come close to this regime, particularly if special attention is paid to searches for anti-helium.

The relatively large abundance of helium in the cosmic radiation is particularly fortunate because helium is cosmologically unique. Most of present day helium is a remnant of the Big Bang, whereas essentially all of the heavier elements have been produced by stellar nucleosynthesis; the heavy antimatter could then only originate in an anti-star condensed from primordial antimatter. Therefore in a scenario in which antimatter was present but never able to condense, cosmological anti-helium could exist without any heavier antimatter, but there is no plausible way for the reverse to be true. Even if an appropriate mechanism did exist to produce isolated heavy antimatter, the heavy antimatter in the cosmic radiation would produce anti-helium by spallation. A specific search for cosmological antimatter should therefore be best undertaken as a search for anti-helium.

Experiments especially optimized to search for cosmic ray anti-helium and heavier anti-nuclei are discussed in Section IV.B.

3. Electrons and Positrons

Electrons and positrons are unique among the charged cosmic particle radiations because of their low rest mass. They interact electromagnetically with the constituents of the interstellar medium, with nuclei by bremsstrahlung, with photons by inverse Compton scattering, and with magnetic fields through synchrotron radiation. Secondary photons from such interactions in the gamma ray region and in the form of nonthermal radio-emission are observed to come from our galaxy and from external galaxies as well. From measurements of the energy spectra of positrons and electrons we expect key information on a variety of astrophysical issues:

Sources and Acceleration: In the energy region where separate measurements of electrons and positrons are presently available (< 20 GeV), a significant excess of negative electrons has been observed. This indicates that most electrons come from primary sources in our galaxy. It is not known, however, whether these sources are the same as those of the nuclear radiations, and whether the energy spectra at the sources are the same for nuclei and electrons, as shock acceleration models would predict. These questions can only be answered if one determines how the energy spectra are altered due to radiative energy losses during propagation.

Distribution of Acceleration Sites: Because of radiative energy losses, electrons with very high energies cannot propagate through large distances in interstellar space. Electrons with energies > 1 TeV lose most of their energy in 10^4 or 10^5 years and can travel at most a few hundred parsecs. Because only a few candidate sources are likely to lie this close to the solar system, measurements of the spectrum and arrival direction of electrons with energies >1 TeV may reveal the presence of nearby cosmic ray sources.

Interactions in Interstellar Space: Cosmic ray electrons can be produced in interstellar space as secondary products of nuclear interactions (mainly through the $\pi \rightarrow \mu \rightarrow e$ decay chain which generates about equal abundances of secondary electrons and positrons). It is believed that all positrons are produced in this way, while the much larger flux of negative electrons receives essential contributions from primary acceleration sites. Hence, the flux of positrons is a measure of the amount of interstellar matter traversed by primary nuclei (mostly protons). Comparison of the positron measurements with the abundances of other secondary particles (antiprotons, ^{2}H and ^{3}He, the light elements Li, Be, and B, and the sub-iron elements) over a wide energy range will provide a detailed description of the matter traversed by cosmic rays propagating through the interstellar medium.

Containment Time: Electrons in interstellar space either escape from the galaxy or lose their energy by radiative processes. At high energies, the

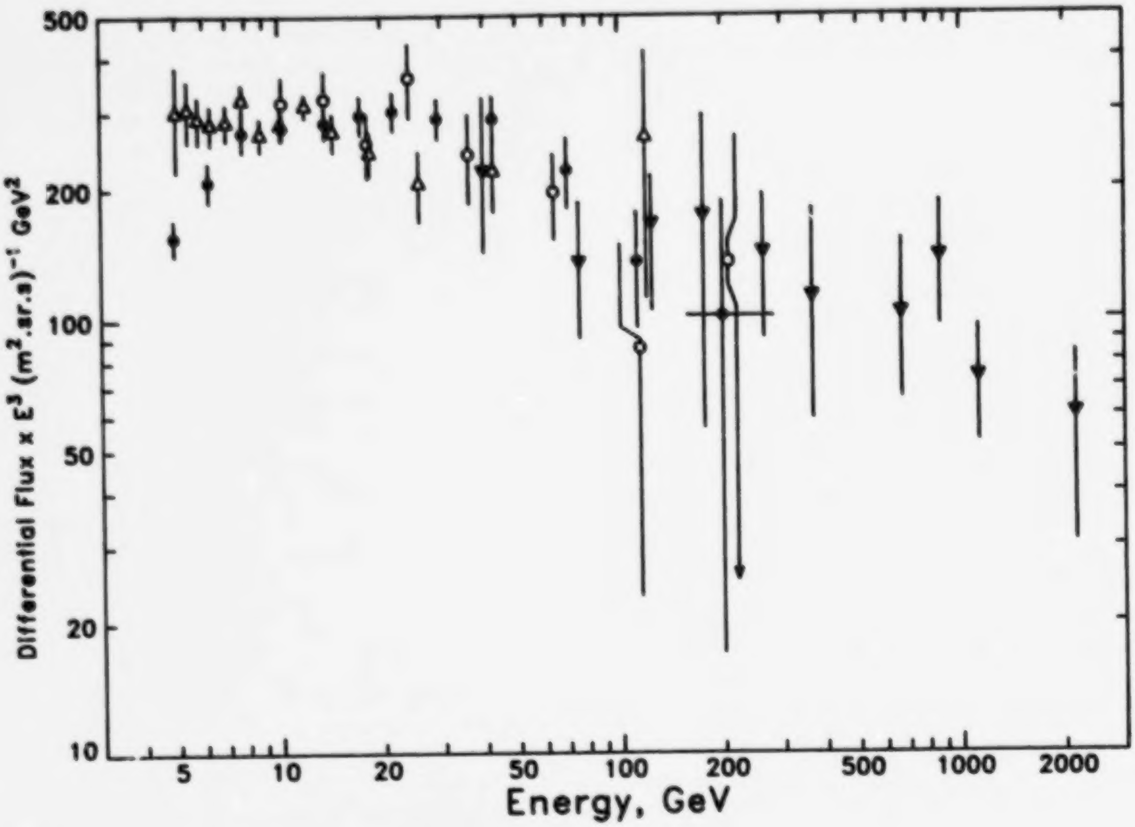

Figure II-3: A summary of recent measurements of the flux (multiplied by E^3) of cosmic ray electrons (negative electrons plus positrons).

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rate of energy loss (which is proportional to E^2) will dominate, and will lead to a steepening of the measured energy spectrum. The observation of this effect permits the determination of the galactic containment time of electrons. On the basis of present data (see, e.g., Figure II-3), a steepening of the spectrum around 10-30 GeV is interpreted as evidence of a containment time of about 10^7 years. However, this interpretation is open to question as the source spectrum of electrons is not known. Separate measurements of positive and negative electrons should resolve this problem since the source spectrum of the (secondary) positrons is known. Some recent measurements indicate an increase in the positron fraction near 10 GeV, just the energy where the overall spectrum steepens (see Figures II-3 and II-4). If verified, these results might indicate that the steepening of the electron spectrum is peculiar to the source rather than being a consequence of energy losses during propagation.

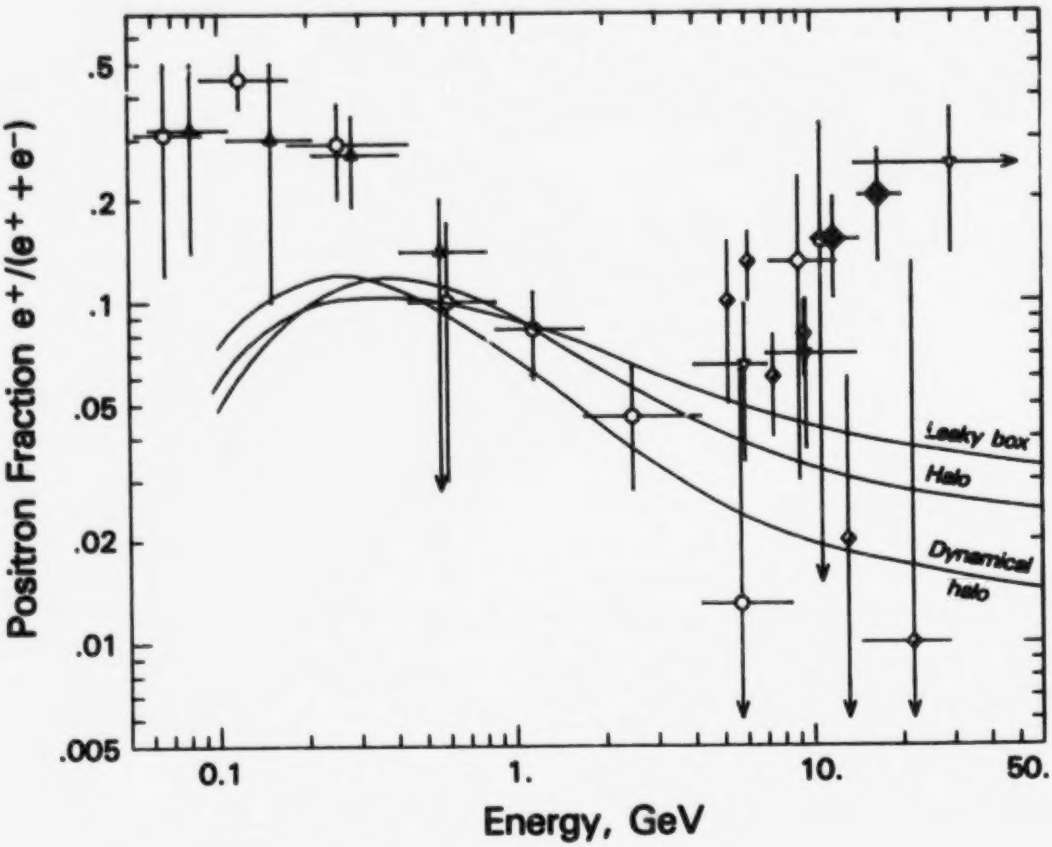


Figure II-4: Measurements of the positron to total electron ratio are compared with the predictions of three cosmic ray propagation models.

Galactic Magnetic Fields and Galactic Halo: The rate of radiative energy loss by electrons is a sensitive function of the energy densities of the magnetic fields ($B^2/8\pi$) in the galaxy and in the galactic halo. Measurements of the non-thermal radio emission of the galaxy already indicate that the halo contributes to the containment of electrons. Eventually, the interpretation of the energy spectra of electrons and positrons must provide a self-consistent description of both the distribution of acceleration sites and the large scale structure of magnetic fields throughout our galaxy. This description must be consistent with radio measurements and with measurements of the diffuse galactic gamma-radiation (which receives contributions from inverse Compton scattering of electrons on starlight and on the black body radiation).

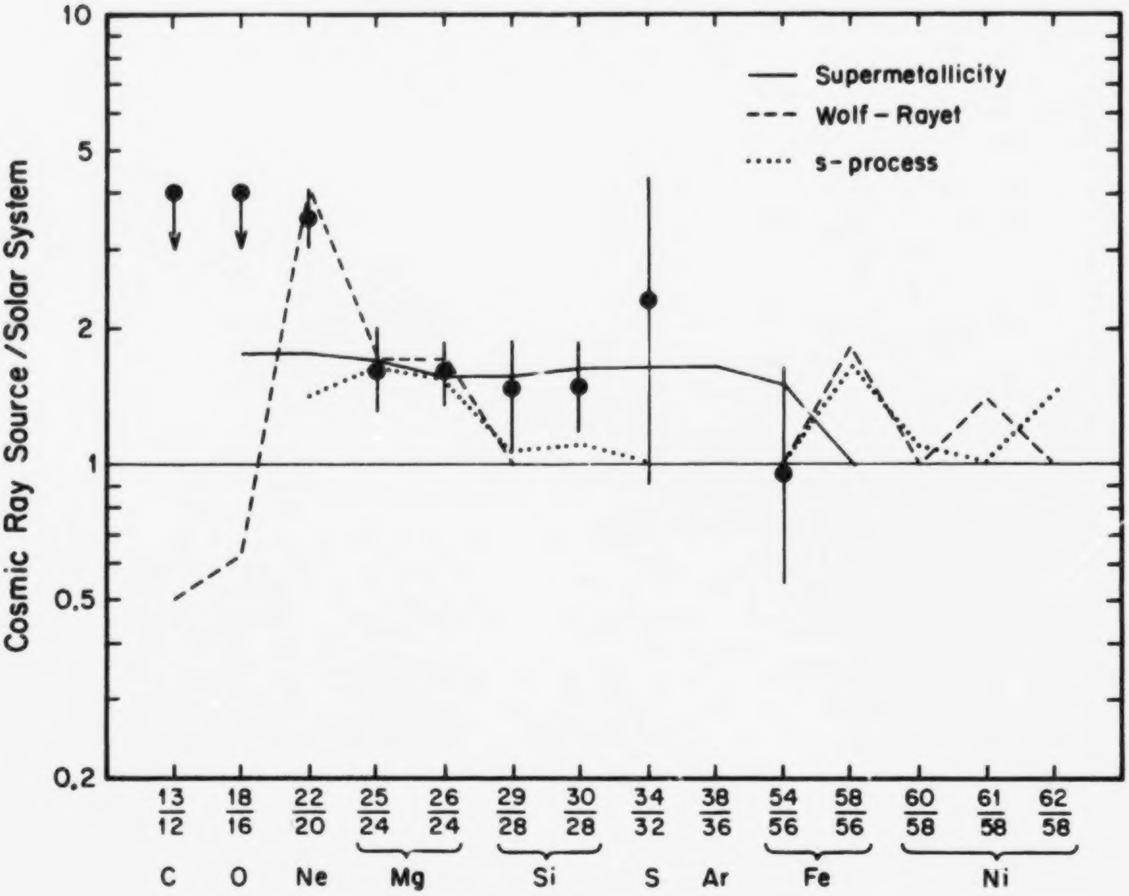


Figure II-5: A compilation of recent determinations of the isotopic composition of the cosmic ray source normalized to the solar system composition. Predictions are shown for three models that have attempted to explain the observed excess of neutron-rich Ne, Mg, and Si isotopes in cosmic ray source material.

A strawman experiment that could provide separate measurements of the spectra of both electrons and positrons over the energy range from 5 to 1000 GeV is described in Section IV.A. In addition Section IV.C discusses electron and positron measurements that might be obtained in a high-latitude STS flight of Astromag.

4. Isotopic Composition

The isotopic composition of galactic cosmic rays contains a record of the nuclear history of a sample of matter from other regions of the galaxy,

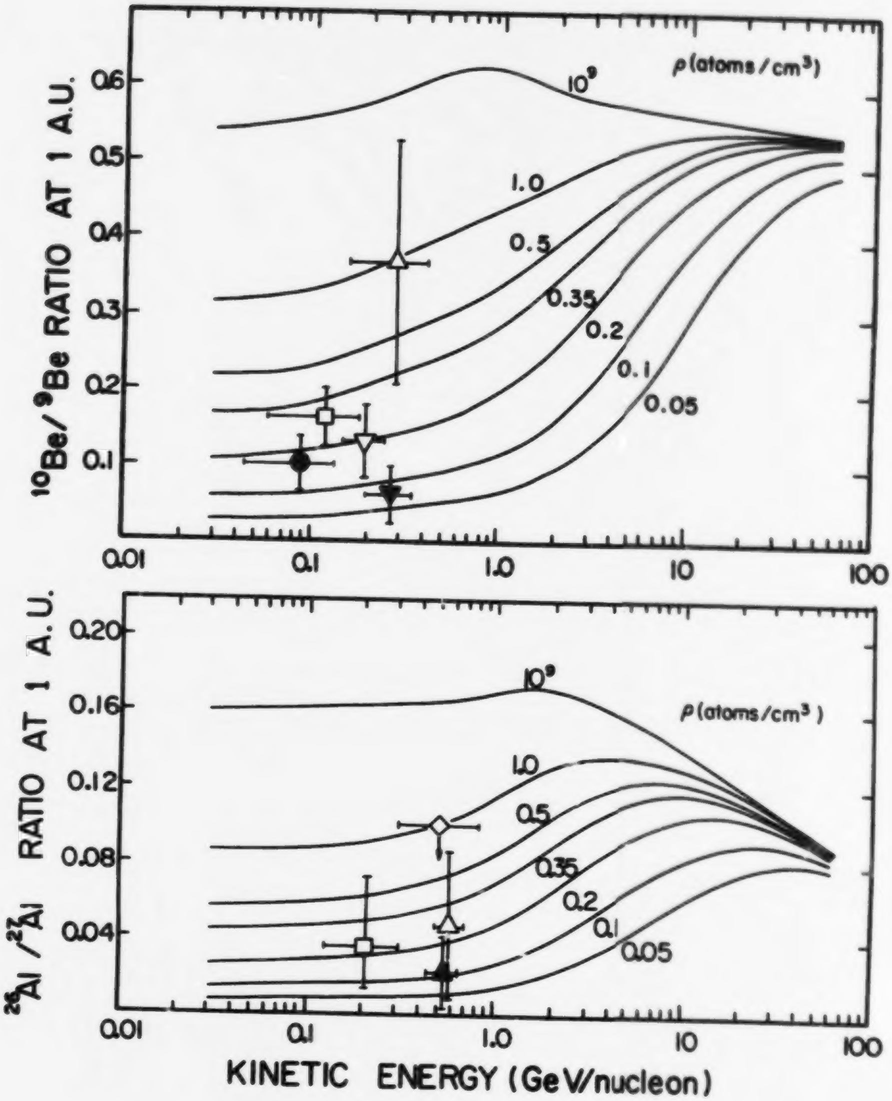


Figure II-6: Measurements of the cosmic ray ^{10}Be/^{9}Be and ^{26}Al/^{27}Al ratios are compared to the predictions of a standard propagation model, parameterized by the mean density (ρ, in atoms/cm^3) of the material traversed. The mean cosmic ray lifetime in this model is inversely proportional to the density. Thus, for example, relativistic (β=1) cosmic rays with a mean pathlength of λ = 5 g/cm^2 have a mean lifetime of $T = \lambda/\beta c\rho \approx 10^7$ years if ρ = 0.3 H atoms per cm^3.

including its synthesis in stars, and its subsequent nuclear interactions with the interstellar gas. One of the most exciting prospects for Astromag is the opportunity to extend measurements of cosmic ray isotopes to the energy range from about 2 GeV/amu to well beyond 10 GeV/amu. At these high energies, the interpretation and understanding of the measurements is helped by the fact that the fragmentation cross sections become essentially independent of energy, that solar modulation has a relatively small effect on the energy spectra, and that the decreasing interstellar pathlength reduces the contributions of secondary cosmic rays.

Recent observations of enhanced abundances for the neutron-rich Ne, Mg, and Si isotopes in cosmic rays have shown that cosmic ray source material is distinctly different in isotopic composition from typical solar system matter. In particular, it has been observed that ^{22}Ne is at least a factor of 3 times more abundant in cosmic ray source material than in solar system material, while the cosmic ray abundances of the neutron-rich isotopes ^{25}Mg, ^{26}Mg, ^{29}Si, and ^{30}Si are all enhanced by a factor of approximately 1.5.

This anomalous isotopic composition implies that the nucleosynthesis of cosmic ray and solar system matter has differed, a discovery that has stimulated a number of new theoretical suggestions as to how such differences might have occurred. These include: (1) the possibility that cosmic rays represent a more evolved sample of matter, possibly from metal-rich regions of the galaxy; (2) the possibility that cosmic rays originate in a limited class of objects, such as supernovae or Wolf-Rayet stars; and (3) the possibility that the solar system composition is anomalous with respect to the bulk of galactic material as a result of events associated with its formation. Figure II-5 compares presently available measurements with the predictions of three proposed models. Isotopic studies of rare isotopes such as ^{13}C, ^{18}O, ^{34}S, ^{38}Ar, ^{54,58}Fe, and ^{60,62}Ni are required to see how this pattern of isotopic differences extends to other elements so that the nucleosynthetic origin of cosmic ray material can be determined. Astromag could provide a factor of about 100 improvement in yield over presently available isotope data, permitting the source abundance of even rare isotopes to be determined. A fundamental question of cosmic ray astrophysics is whether cosmic rays represent a sample of freshly-synthesized material, perhaps from supernovae or other objects, or whether they might be much "older", perhaps a sample of the interstellar medium (ISM). This question can be addressed by measuring the time-delay between nucleosynthesis and acceleration using various radioactive isotopes that would decay by electron-capture while at rest (e.g., ^{55}Fe, ^{56}Ni,^{57}Co, and ^{59}Ni) but cannot decay once accelerated to high energies and stripped of their orbital electrons. Isotope measurements to date show that this time delay is 30 days or more (based on the ^{56}Ni to ^{56}Fe decay). Direct determinations of whether the ^{57}Co (half-life = 271 d.), ^{55}Fe (half-life = 2.7 yr,), and the ^{59}Ni (half-life = 8 x 10^4 yrs for electron capture) decays have occurred should discriminate between a supernova and an ISM origin.

High energy isotope measurements also add a new dimension to studies of cosmic ray propagation using radioactive isotopes such as ^{10}Be, ^{26}Al, ^{36}Cl, and ^{54}Mn as natural clocks to determine the storage time of cosmic rays in the galaxy. A unique feature of Astromag is its ability to "read" these clocks over a wide range in energy and corresponding time-dilation factor. Figure II-6 shows how the abundances of ^{10}Be and ^{26}Al are expected to depend on energy and on the average density of material in the cosmic ray confinement region. With Astromag on the Space Station it will be possible to measure the ^{10}Be abundance from 2 to 40 GeV/amu and the ^{26}Al abundance from 2 to >10 GeV/amu, while a high-latitude STS flight would allow the extension of this and other studies down to about 0.4 GeV/amu. Deviations from the simple model shown in Figure II-6 might result if energy-changing processes such as re-acceleration by supernova shock-waves are significant during the approximately 10^7 year storage time of cosmic rays in the galaxy. In addition, a comparison of the cosmic ray "age" measured by clocks with different half-lives would probe the homogeniety of the matter traversed. Some recent studies suggest that much of this material may be in the cosmic ray source region, which may also be the explanation for some high-energy γ-ray sources.

There has recently been renewed interest in the rare isotopes ^2H and ^3He, the dominant secondary products resulting from interactions of primary ^4He. Some models which explain the excess of antiprotons observed in cosmic rays require that cosmic ray H and He have a different origin and history from that of heavier nuclei. Such models also produce excesses of ^2H and ^3He compared with standard models in which all nuclei have the same origin. A comparison of ^2H and ^3He measurements over a broad energy interval with those of heavier secondary species (e.g., Li, Be, B and Fe-secondaries) will determine whether cosmic ray He nuclei have the same origin and history as that of heavier cosmic rays. In addition, since secondary antiprotons are produced only in high-energy (>5 GeV) interactions, it is especially important to have high-energy measurements of ^2H and ^3He for comparison with antiproton and positron spectra to understand whether more exotic sources of antiprotons are required. With Astromag, ^2H and ^3He might be studied from about 2 to beyond 50 GeV/amu.

By combining presently available detector technology with the capabilities of the Astromag core facility, a spectrometer capable of high-resolution measurements of $Z \leq 28$ nuclei with energies of several GeV/amu might be flown on the Space Station. Such an experiment could improve by 2 orders of magnitude on the presently available sample of high-resolution isotope events, adequate to address essentially all of the objectives summarized above. One possible version of such an experiment, designed for nuclei from carbon to nickel with 2 to 6 GeV/amu is described in Section IV.A, while an approach to study lighter isotopes is discussed in Section IV.B. Using essentially the same design, but tuned for lower energies, an STS flight of Astromag in a high-latitude orbit of 57 degrees or greater inclination could provide isotope measurements spanning the energy range from 0.4 to 2 GeV/amu (See Section IV.C). With further development of velocity measuring devices, studies of light isotopes could be extended into the energy region from 10 to 50 GeV/amu. A possible future experiment to exploit this capability is described in Section IV.B.

5. Elemental Composition and Energy Spectra

Through measurement of the magnetic rigidity, Astromag will determine the kinetic energy of each particle traversing the spectrometer. Although other techniques can be used for energy measurements (e.g. calorimeters, Cherenkov counters, or transition radiation detectors), none offers the combination of excellent energy resolution and large energy range that is characteristic of Astromag. Thus, precise measurements of the energy spectra of individual elemental species with Astromag will greatly enhance our knowledge of the cosmic particle radiation at high energy. In most cases, these measurements will be obtained in conjunction with experiments designed to address other objectives (for example, the isotope measurements discussed above) without requiring additional instrumentation.

For instance, it is known from measurements of various "secondary/primary" ratios that cosmic rays above 2 GeV/amu have passed through less material than those with lower energy. This is usually interpreted as energy-dependent confinement to the galaxy with a mean interstellar pathlength that decreases from around 8 g/cm^2 at 2 GeV/amu to only 1 or 2 g/cm^2 at 100 GeV/amu. Precise measurements of the relative elemental abundances covering a large range of energies are required to understand this phenomenon and to distinguish among models of the galaxy that result in energy-dependent cosmic ray confinement.

In addition, measurements beyond 100 GeV/amu may provide the clearest picture yet of the elemental composition of cosmic ray sources, as a result of the greatly reduced extent to which the original composition of these high-energy particles has been altered by fragmentation. It is particularly important to determine whether the source composition depends on energy, and whether, for instance, H and He have different source spectra and a different origin than heavier nuclei. Astromag measurements should make it possible for the first time to study simultaneously the spectra of all elements from H to Ni ($Z = 1$ to 28) over a very broad energy range.

Precise measurements of particle energy spectra are an essential diagnostic tool for identifying the acceleration mechanisms. In particular, it is important to search for structure in the energy spectra, due either to acceleration or propagation effects, which instruments of poorer energy resolution may have been unable to detect. It is possible that special objects emit cosmic ray particles at particular energies, or over comparatively narrow energy intervals.

The lower end of the energy range over which Astromag will be able to measure elemental composition is determined by the geomagnetic cutoff, roughly 2 GeV/amu in the Space Station orbit. It is bounded at high energies by the maximum detectable energy of the magnet facility, about 500 GeV/amu if one wishes an energy resolution of 10% or better. Assuming a geometry factor of several tenths of a m^2sr, and an exposure time of a year, about 5×10^4 carbon, 10^4 iron, and somewhat fewer than 10^3 nuclei of each iron secondary species could be collected above 100 GeV/amu. This would provide for a measurement precision that will not have been accomplished in any previous experiment.

C. FURTHER OPPORTUNITIES

The previous section describes some of the most significant scientific objectives in particle astrophysics whose pursuit requires the availability of a magnet spectrometer facility. Meeting the basic requirements of these experiments must be a leading consideration in the design of Astromag. However, the capabilities of Astromag are not restricted to these goals, but provide opportunities for scientific ventures and the potential for fundamental discoveries in a number of related or entirely different fields of inquiry. While it is impossible at the present time to foresee all possible developments, the following ideas give an indication of the range of opportunities.

1. High Energy Gamma Rays

The satellites SAS-2 and COS-B have made observations of celestial γ-rays up to about 1 GeV. In the late 80's or early 90's the Gamma Ray Observatory (GRO) will extend these observations to 10 or 20 GeV. In addition, ground-based detectors have observed gamma-rays in the energy range above 1 TeV (10^{12} eV) (air Cherenkov detectors) and $> 10^{15}$ eV (Fly's Eye and air shower arrays). At these extreme energies, point sources such as Cygnus X-3 have been discovered. The significance of these discoveries is now only beginning to emerge.

In the future, ground-based detectors can be expected to reduce their detection threshold down to 10^{11} eV, with an angular resolution limit of about 1 degree, but there will remain an unexplored gap in the electromagnetic spectrum between about 10 and 100 GeV.

The Astromag facility offers an opportunity to bridge the gap between ground-based and space-borne γ-ray observations by offering a new method to identify the electron-positron pair that is typically produced in the interaction of a high-energy γ-ray with matter. Within the field of the magnet the energetic electron and positron will separate and bend in opposite directions. Using the trajectory information provided by the spectrometer, the pair-production signature can be easily recognized, the energies of the pair can be individually measured, and the direction of incidence of the primary photon can be determined with high precision (several arc minutes).

Thus, with appropriate implementation of this approach, Astromag could measure the diffuse galactic gamma ray emission from 1 to 100 GeV, and should permit very precise identification of point sources. Since it would be awkward to mount Astromag on a platform with celestial pointing capability, its principal mode of operation for γ-ray observations would be celestial scanning, and its intrinsic capability of achieving a large field of view would be important to obtain good sky coverage. Due to the excellent energy resolution that is expected, Astromag could be used to detect spectral features or high-energy γ-ray lines. For example, it has been suggested that the annihilation of weakly interacting massive fermions (WIMFs) leads to sharp γ-ray lines in the GeV region. Thus, the capabilities of Astromag could make possible fundamental if unexpected discoveries of great significance.

With minor modifications, the Matter/Antimatter Spectrometer described in Section IV.A could detect γ-rays in the 1 to 100 GeV energy region with unprecedented energy resolution and excellent angular resolution, providing the first test of this new approach. A possible approach to a much larger Astromag experiment devoted to high-energy γ-ray astronomy is discussed in Section IV.B.

2. Nuclear Physics and Searches for Exotic Particles

All of the particles identified at the present time in the primary cosmic radiation have also been well known in laboratory experiments for many years. However, detectors operated in space have until now been very limited in size and weight, restricting their abilities to search for new, exotic particles. The combination of high magnetic field and large area in the Astromag facility offers the possibility of significantly extending the frontier for discovering particles which are presently unknown. Presumably, any such exotic particle or nucleus would be stable or long-lived in order to reach the Earth, but its interactions with the atmosphere might well prevent its discovery at ground level. There have been numerous proposals for hypothetical exotic particles amongst the cosmic ray primaries, some of which also attempt to account for the 'dark matter' of the galaxy; presently the suggestion that nuclear matter may have another stable form, strange quark matter or nuggets, has evoked widespread interest and study by nuclear physicists and astrophysicists.

Astromag could also facilitate studies of nuclear interactions of primary cosmic ray particles or nuclei with various target nuclei. Cosmic ray interactions with energies much greater than the highest accelerator energy can be observed, which may lead to the discovery of new collision phenomena. For instance, there is at present a controversy over the validity of scaling laws in high energy collisions which could be addressed with measurements made on Astromag. A possible design for a detector to undertake this search is described in Section IV.B.

3. Solar, Solar-Terrestrial, and Heliospheric Studies

The large-area, high-resolution detectors that will be employed with Astromag will be capable of measuring time-intensity variations of a variety of cosmic ray species with very good statistical accuracy, and they will also be sensitive to high-energy particles accelerated during large solar flare events. Although the potential for such observations is unlikely to be a driving consideration in the design of Astromag instrumentation, many of the experiments under consideration will undoubtedly also produce valuable data for addressing important solar-terrestrial-heliospheric problems, as illustrated by the following examples.

Experiments on Astromag will have an energy threshold for observing solar flare particles similar to that for neutron-monitor observations of "ground-level" solar flare events, including (over parts of its orbit) thresholds of 4 GeV for protons and 2 GeV/amu for alpha-particles. Thus, for occasional very large solar flare events, Astromag may extend direct measurements of energy spectra into the GeV region, and, for example, search for a cutoff in the spectra such as might result from the finite size of the acceleration region.

It is likely that any of the Astromag instruments capable of identifying high-energy γ-rays (see Section IV.B.4) may also be sensitive to neutrons with energies greater than 100 MeV, and in some cases the incident energy of the neutron can be accurately determined. Transient fluxes of such neutrons are produced in large solar events, and carry information on the time history of the acceleration of the highest-energy flare particles, to be compared with x- and γ-radiation that reflects the time-history of lower-energy species. Thus Astromag may provide improved measurements of the high-energy neutron production spectrum and time-profile in large solar events.

The large collecting power of Astromag instruments will necessarily result in precise measurements of the temporal variations of a variety of cosmic ray species. Such observations would overlap in energy with ground-based measurements provided, for example, by neutron monitors, but they would have the advantage of being available for individual species (e.g., protons, alpha-particles, electrons, and positrons) as a function of energy. These data would be very useful for studying solar modulation problems; for example, they could provide a sensitive measure of the extent to which solar modulation depends on the sign of the particle charge. Astromag data might also be used to search for anisotropies in the flux of high energy protons and electrons that are predicted to result from transport in the heliosphere.

4. Plasma Physics Experiments

The strawman magnet configuration for Astromag includes a high intensity cusp magnetic field between the two coils with an intensity of several Tesla. If the cryostat could be designed to give access to this region, it would be possible to develop plasma physics experiments using the high flux cusp field.

These experiments will be unique, offering capabilities not available on Earth. These experiments will address issues of the plasma environment of the Space Station and allow fundamental plasma physics studies which had not been addressable in the laboratory programs. The need for such studies has most recently been restated by the Panel on the Physics of Plasmas and Fluids of the National Research Council in "Physics through the 1990s" where they call for controlled study of the plasma environment of the Earth through the systematic use of active experiments. The principal studies are:

1. Use of a variable species (and temperature) plasma generated locally to investigate
    - a. plasma flows around and about the space platform;
    - b. turbulent mixing of plasma from different sources (e.g., locally generated and environmental); and
    - c. the long wavelength spectrum of convecting modes.
2. Use of the field geometry as a plasma collector to permit measurement of local plasma properties, space potential, temperature and flux, as well as mass and charge analysis of low abundance plasma species.
3. Use of the microgravity environment and controlled local plasma source to examine plasma-dust interactions.

Most of these studies must be performed in space; flow perpendicular to the local magnetic field with plasma parameters suitable for the proposed studies have not been generated in the laboratory, making study '1a' unique to the Space Station; study '1b' is generally not available on Earth and the large scale lengths are extremely favorable for '1c'; the other studies directly relate to the space environment. Studies '1a, b, c' contribute to our understanding and ability to predict turbulent convective transport in the ionosphere and near-Earth regions. Although identical conditions are difficult to duplicate, aspects of these studies complement and would be complemented by laboratory "co-experiments". These areas of investigation could benefit greatly through the development of these new techniques and experimental programs.

A controlled, variable species plasma can be made in various field geometries all of which require a field on the order of a Tesla, by using an RF ion source with adequate gas efficiency. The need for efficient gas utilization in the plasma source normally implies buildup of the plasma density in a confined volume in order to obtain multiple pass heating and reaction rates. Thus, the natural location for the plasma source would be the central region of the cusp where there exists a ~ 1/2 m diameter volume. Heating on the outside of the cusp would necessarily be only single pass, unless the line cusp field is slightly modified to provide a suitable confining region. This appears to be possible with the use of external passive elements; for example, a double stranded iron girdle might be placed about the line cusp to create a local (azimuthally symmetric) field minimum with a maximum further outside or alternately, permanent magnets could be used to create the external symmetric magnetic mirror. The microwave generated plasma would be expected to have the characteristics indicated in Table II-1 for 1kW input power (depending on the type of heating). For electron cyclotron heating, the resonance zone is restricted (because of limitations on microwave power generation) to regions where the field intensity is < 1 Tesla.

Table II-1

Heating	T_i(eV)	T_e(eV)	N_e(cm^{-3})
Ion Cyclotron	10 - 50	~ 10	~ 10^{11}
Electron Cyclotron	~ 5	10 - 100	~ 10^{11}

In actual operation, interference with other subsystems is minimized as plasma physics experiments are of short duration and would have a low duty cycle.

III. MAGNET FACILITY

A. OVERVIEW

Observations of the deflection of charged particles in a strong magnetic field are essential to the observations discussed in the previous section. The deflection is inversely proportional to the particle's momentum per unit charge or magnetic rigidity, $R=mc^2\beta\gamma/q$, where βc is the particle's velocity, γ is its Lorentz factor, m its mass and q its charge. Thus when combined with independent measurements of the particle's velocity and of the magnitude of its charge, magnetic deflection measurements can be used to deduce the mass and the sign of the charge. Conversely, if the charge is independently determined, the magnetic deflection can provide a precise measurement of the particle's momentum. When particle momenta are expressed in units of eV/c and charges are in units of the elementary charge, e, one obtains the volt (or gigavolt, GV, or teravolt, TV) as the basic unit of magnetic rigidity.

Figure III-1 illustrates schematically the principles involved in the determination of a particle's rigidity. Expected trajectories through a realistic magnetic field (see Section III-B) are shown for three types of particles: the two isotopes of helium (^{3}He and ^{4}He), and the anti-^{4}He nucleus, $\bar{\alpha}$. These particles are all taken to be incident on the top of the spectrometer at the same position and with the same vector velocity (corresponding to an energy of 5 GeV/amu). As illustrated in the figure, the identities of these particles are readily distinguished by the differences in their trajectories--the more massive particles, ^{4}He and $\bar{\alpha}$, are deflected less than the lighter ^{3}He, while the particles ^{4}He and ^{3}He are deflected in the opposite direction from the anti-particle, $\bar{\alpha}$, due to the opposite signs of their charges. These particle identifications based on trajectories depend on a precise knowledge of the particle velocities, which must be provided by additional detectors specific to individual experiments (see Section IV).

As the rigidity, R, of the particles being studied increases, the deviation of the trajectories from a straight line decreases (proportional to 1/R). At a certain rigidity this difference becomes too small to be distinguished with the finite spatial resolution of the position sensing (trajectory) detectors. This limit, which depends on the path of the particle through the magnetic field and also on the characteristics of the trajectory measuring system, provides a useful parameter for characterizing the performance of the spectrometer. This quantity, called the 'maximum detectable rigidity', is denoted as MDR, or R_{max}, and is expressed in volts. For a typical trajectory system where each detector plane has 50 μm spatial resolution, used in conjunction with the planned magnet, a distribution of maximum detectable rigidities is obtained which extends up to approximately 3 TV. R_{max}, formally defined as the value of the rigidity at which the fractional uncertainty in R^{-1} becomes unity, is used to characterize the resolution of the spectrometer at any rigidity. The fractional uncertainty in the determination of rigidity can be expressed as $\sigma_R/R = R/R_{max}$. Thus, for example, if one wishes to measure the rigidity of a 3 GV nucleus to a precision of 0.1%, one must utilize those regions of the spectrometer which provide an R_{max} greater than 2 TV.

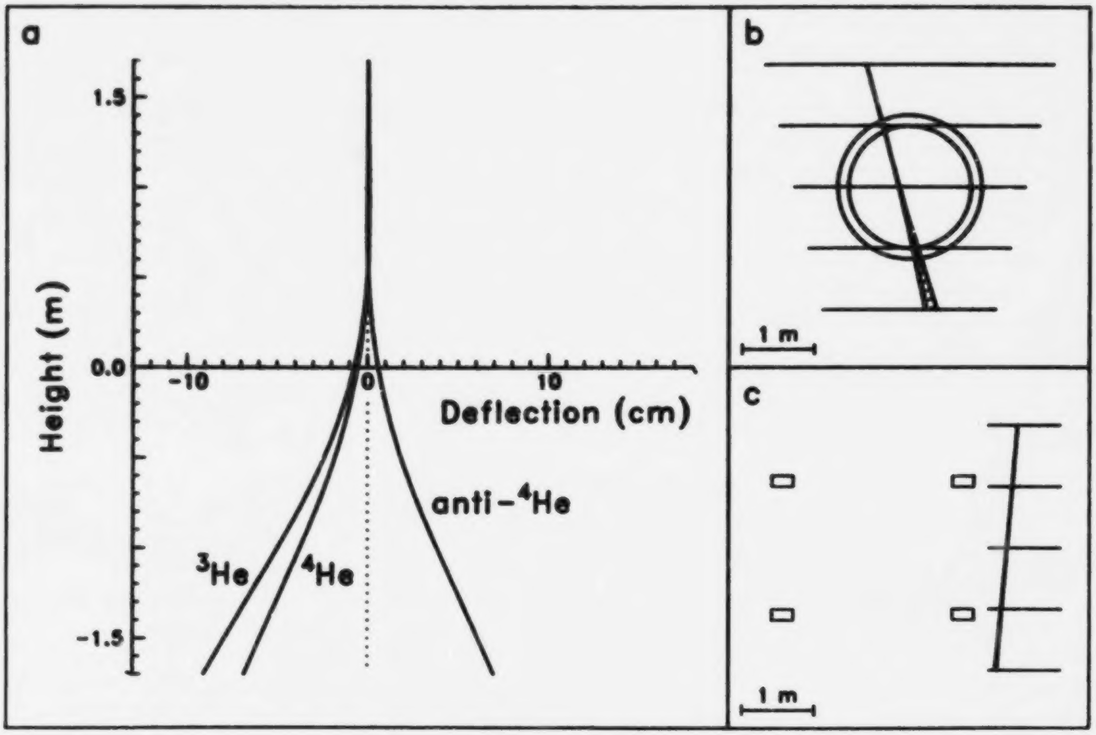


Figure III-1: Cartoon illustrating actual trajectories of 5 GeV/amu ^{3}He, ^{4}He and $\bar{a}$ in magnetic field of HEAO magnet.

Because Astromag's experimental objectives all require a measurement of each particle's rigidity, a core facility is planned which will provide a large volume of strong magnetic field and a basic data handling system for control, maintenance and calibration of the magnetic spectrometer. The facility will also perform the data collection and interfacing functions for the experiments.

Besides the magnetic field, the other element required by all experiments is an array of precise position sensing detectors for determining the trajectories of charged particles through the field. Experiment integration and calibration are simplified if the trajectory sensors are constructed as part of each particular experiment, rather than as a permanent component of the core facility. However, the detectors and technology developed for the first experiments will be available for subsequent experiments. New experiment teams will then have the option either of constructing position sensing detectors of proven design, with adaptations as needed to meet unique requirements, or of employing trajectory arrays which have already been built and tested.

In addition to the basic functions which the core facility must provide for any experiment, several other elements may be common to a number of experiments. Among these are: 1) A time-of-flight detector system that distinguishes between upward-moving and downward-moving particles in the spectrometer. This capability is important for background rejection in many of the envisioned experiments. 2) A set of large area trajectory detectors with coarse resolution to be positioned above and below the rest of the experimental apparatus that provide a fast and simple first level trigger based on approximate particle charge and deflection. Such a trigger would, in some experiments, allow a substantial reduction in the number of background events to be processed (for example, the proton background in an antiproton experiment). 3) A large area ionization detector or Cherenkov counter to identify the particle charge and, in the case of a Cherenkov counter, provide a velocity threshold useful for rejection of low energy background events. This function could be provided by the fast trigger system mentioned above, by the high resolution track detectors in the spectrometer, or by a separate set of detectors.

In the following subsections plans are discussed for the major components of the facility: the magnet system, the trajectory measurement system, and the data system.

B. MAGNET

The heart of the charged particle detection and resolution system for Astromag is the superconducting magnet. The scientific capabilities of the facility depend in important ways on the size, shape, and placement of the magnet coils. The coil configuration in turn strongly influences the cost and complexity of the facility. A variety of coil configurations have been compared to make a preliminary evaluation of the trade-offs between capabilities and complexity.

These comparisons were based on a number of assumptions and constraints, as follows:

- The dimensions and weight of the coils, dewar and stored cryogen are limited to a size which will permit simultaneous launch of the core facility and two initial experiments, with final assembly to be completed on orbit. Typical magnets considered fit in a cylindrical envelope 2 m in diameter by 2 meters in length, and have a mass less than 2000 kg.
- Of this mass, approximately 600 kg is allocated as 'active coil mass'. That is, the mass of the coil plus shorted secondary circuits in which the magnetic energy would be deposited should the magnet quench. Safety considerations then imply a maximum energy stored in the magnetic field in the range of 10 MJ.
- The net magnetic dipole moment is required to be zero so that the interaction with the Earth's magnetic field will produce no significant torques on the Space Station. This requirement is met by employing two or more coils arranged so that the vector sum of their individual dipole moments vanishes. This configuration also causes the fringe magnetic field to decrease to the level of the Earth's field in a reasonable distance (approximately 15 meters).

- The coil will utilize a proven, reliable superconductor consisting of multifilamentary niobium-titanium in a conducting matrix. This superconductor, operated at a temperature of 4.4 K, requires that the magnetic field strength in the superconductor be limited to a maximum of approximately 7 Tesla. The normal operating temperature will be less than 2 K, making the helium superfluid and providing additional safety margin.

- The magnet will be operated in persistent mode. That is, the coils will be charged to their nominal operating currents using an external power source and then electrically isolated to maintain the field without additional power input. The charging process will require the use of either retractable electrical leads or a magnetic flux pump.

- The dewar used to maintain the coils at liquid helium temperature will be designed to permit up to 2 years of operation between cryogen refills. It will be housed in a vacuum shell to permit operation on the ground.

As the basis for preliminary studies of experiments which will utilize the magnet, we have adopted a design which is technically conservative but capable of making major scientific advances in a number of areas. This strawman magnet design is illustrated in Figure III-2. It consists of two identical coaxial coils which carry currents in opposing senses to cancel the individual dipole moments. The space between the coils is occupied by the cryogen dewar, which also provides the mechanical structure to support the repulsive forces between the coils. This arrangement, in which the coils share a common vacuum vessel and thermal isolation system with the helium storage tank, results in a simple dewar of minimum mass. The regions at the two ends of the dewar, just outside the coils, provide the volumes of high magnetic field required for experiments. Figure III-3 shows plots of the pattern of magnetic field lines and of contours of constant magnetic field strength for this coil configuration. The strength and direction of the magnetic field in the region that will be occupied by the trajectory detectors (indicated in Figure III-3) is non-uniform, resulting in complex particle trajectories. However, the techniques for fitting the tracks of high energy charged particles in non-uniform magnetic fields are well developed and can, with precise mapping of the field, provide the rigidity resolution theoretically set by the field strength and the resolution of the trajectory system. This coil configuration allows the placement of experiments in regions where the field of view is nearly unobstructed by the mechanical structure of the magnet, thereby optimizing the use of the available magnetic field.

This coil configuration is well understood from previous studies. The superconducting magnetic spectrometer experiment planned as part of the HEAO satellite program (and not flown, as the result of redirection of the HEAO program in 1973) employed a very similar configuration, albeit about 2.5 times smaller than the magnet considered here. As a result of this similarity, coil configurations of this type are commonly referred to as 'HEAO magnets'. Studies of the original HEAO magnet were carried through to the construction of a prototype coil and a thermal model dewar. These were extensively tested over a period of years and have demonstrated that the desired field strength and design lifetime can be achieved for Astromag. In addition, these studies addressed a number of the technical questions related to cooling, charging, and persistent-mode operation of superconducting magnets in space. Additional experience has been gained through the continuing use of single coil superconducting magnets in balloon-borne particle astrophysics experiments.

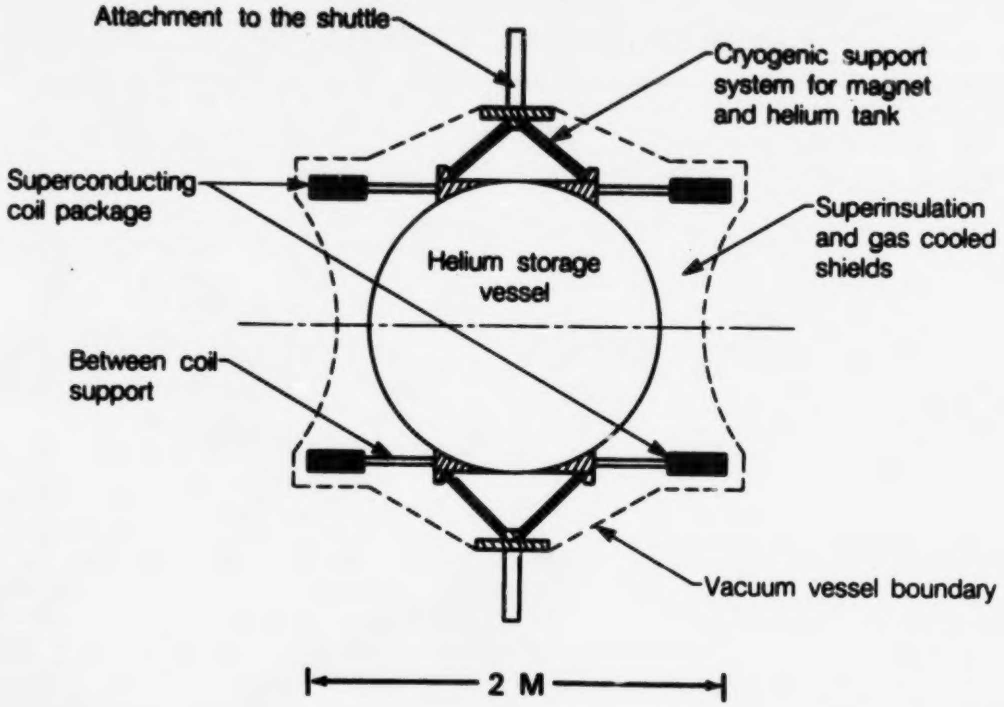
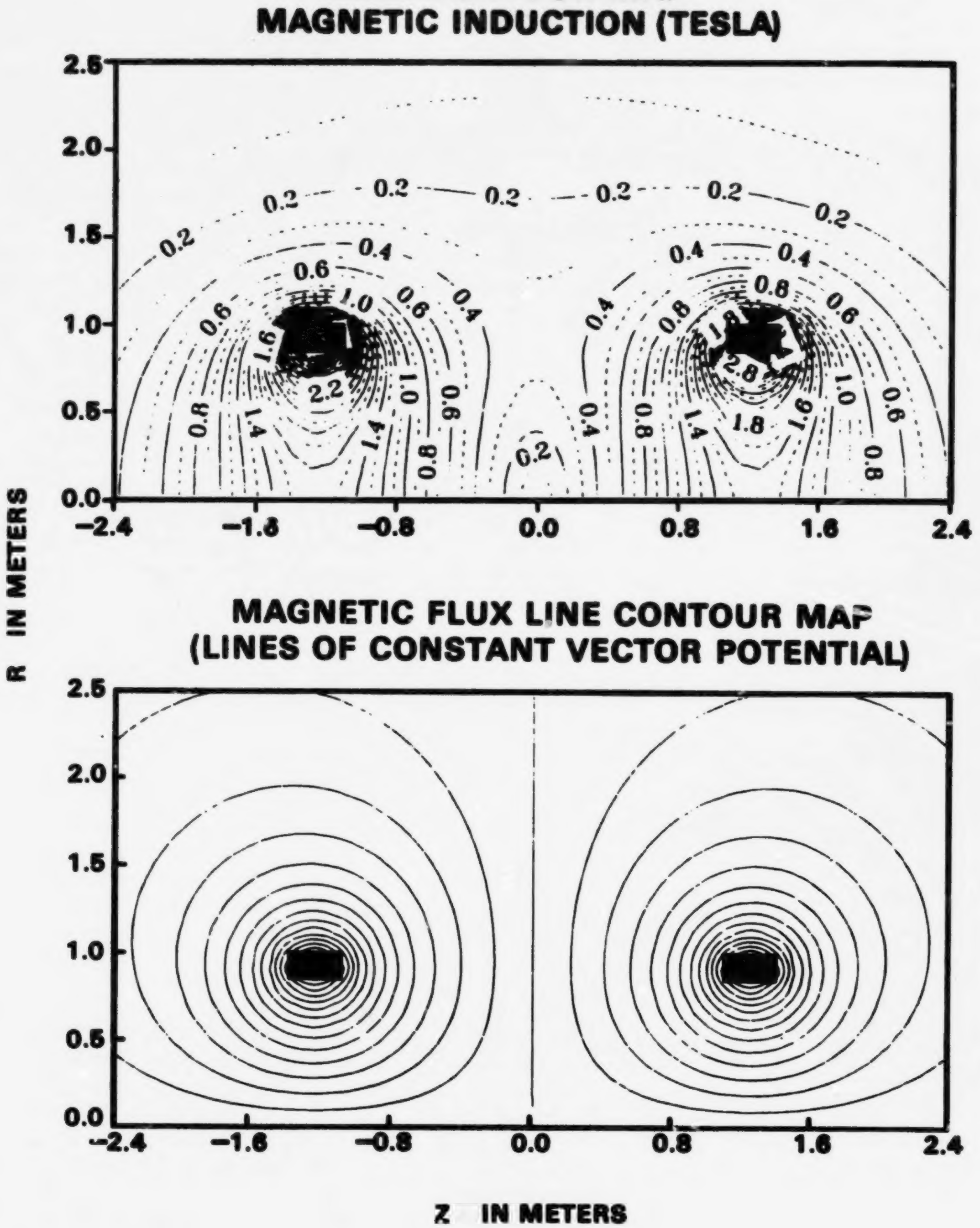

Attachment to the shuttle
Cryogenic support system for magnet and helium tank
Superconducting coil package
Superinsulation and gas cooled shields
Helium storage vessel
Between coil support
Vacuum vessel boundary
2 M

Figure III-2: Isometric, cut-away, illustration of strawman magnet.

In general, the technology required to produce the magnet system is well developed and does not involve major advances beyond the present state of the art. However, multiple options and alternatives are available in several areas of the design and operation of this device, and detailed studies are planned to evaluate the various trade-offs and to further optimize the HEAO-type magnet for astrophysical experiments. The relationship between stored magnetic energy and active coil mass will be investigated in order to provide the maximum magnetic deflection within the bounds set by weight and safety considerations. The shape and thickness of the dewar and outer vacuum shell in the region outside the surfaces of the coils will be studied in an effort to minimize the distance between the coils and the active area of the trajectory detectors in order to optimize the use of the regions of highest magnetic field strength. Alternative techniques for providing cooling to the coils--immersion in the liquid helium, conductive cooling without immersion, helium pumping to isolated coils--will be investigated, as will their implications for dewar mass, for retention of the cryogen in the case of a quench, for the need to develop pump technology, and for the choice between the use of normal or superfluid helium. Techniques for charging the coils and switching into the persistent mode involving retractable electrical leads or a magnetic flux pump will be studied.



FIELD CONTOUR MAP
MAGNETIC INDUCTION (TESLA)

MAGNETIC FLUX LINE CONTOUR MAP
(LINES OF CONSTANT VECTOR POTENTIAL)

Figure III-3: Magnetic flux line (lower panel) and field (upper panel) contour maps for a 2 m diameter magnet. The R=0 axis is an axis of symmetry.

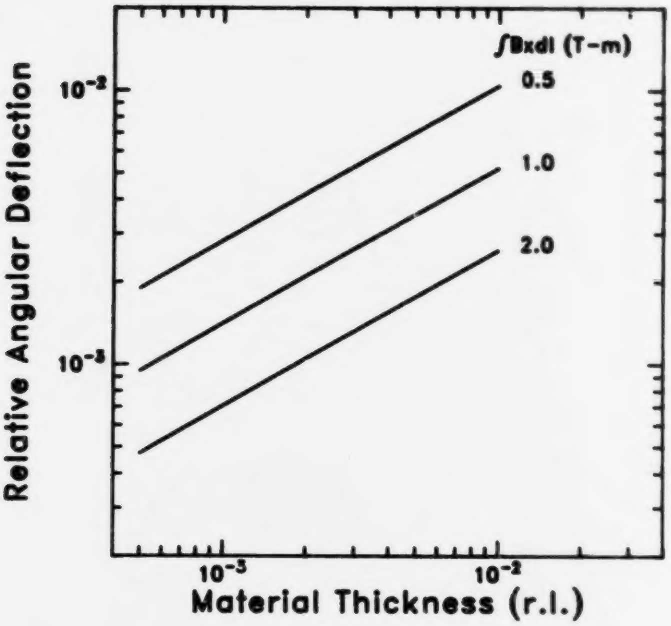


Figure III-4: Relative angular deflections due to multiple scattering and magnetic bending as a function of ∫Bxdl and matter thickness.

In an effort to further enhance the capabilities of the facility for astrophysical investigations, a number of other coil configurations have been considered. Of these, at least two offer appreciably larger geometrical acceptance for high-R_{max} trajectories compared with a HEAO-type magnet having the same stored energy. The alternative designs in which this improvement in resolution can be obtained are, however, more complex than the strawman HEAO magnet system. More quantitative studies are needed to determine whether these designs will remain attractive candidates once the full range of requirements has been evaluated. In the Appendix two alternative coil configurations are described.

C. TRAJECTORY SYSTEMS

In addition to a long path through a strong magnetic field, the magnetic spectrometer requires position sensing detectors capable of precise particle trajectory measurements. In order to meet the scientific objectives of Astromag, the trajectory detector system should have a position resolution of 50 μm or better, sampling over a pathlength of 3 m or more. Each position detector must cover an area of 1-2 m^2. In addition, as illustrated in Figure III-4, energetic particles passing through the material in or between position sensing detectors can be deflected by multiple Coulomb scattering (or, in the case of protons, antiprotons, and to some extent alpha particles, by single scattering

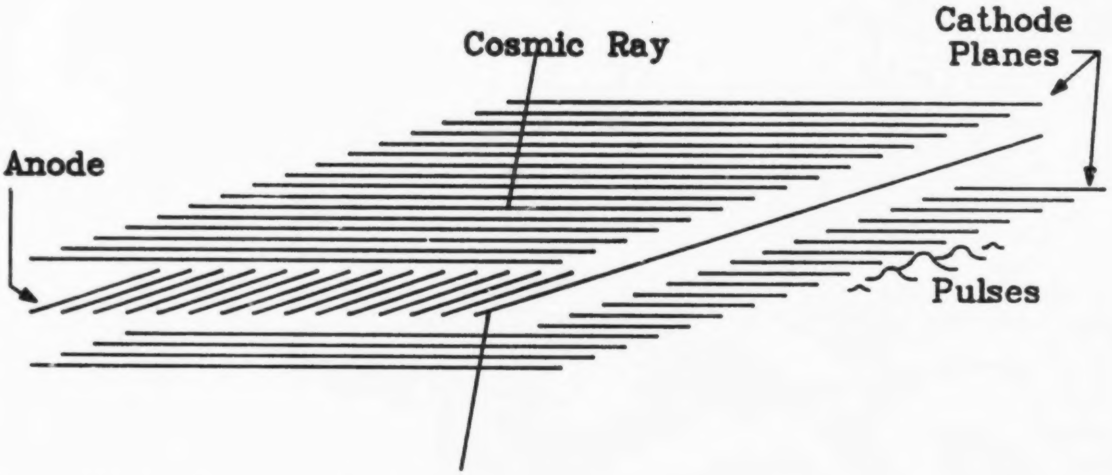


Figure III-5: Cross-Section of a Multiwire Proportional Counter. A cosmic ray penetrating a MWPC leaves a trail of ionized atoms and free electrons. The free electrons drift rapidly towards the positively charged anode wires. They create a large number of additional ions as they are accelerated in the strong electric fields near the anode wires. The cloud of positive ions resulting from this "avalanche" is then attracted by the negatively charged planes. The resulting signal on the cathode wires indicates the location of the particle's track. Measurement of the individual pulse-heights allows determination of this location with an accuracy much better than the cathode wire spacing.

in strong interactions). Therefore the amount of matter in the particle path must be kept to a minimum to avoid scattering which can simulate rare event types. For example, protons can scatter and simulate antiproton-like curvatures, or ^{56}Fe nuclei can scatter and simulate normal ^{57}Fe events. An optimized detector provides minimum mass for scattering at the same time providing background rejection through redundant coordinate measurements.

There are at least two distinct types of position sensing detectors which will be suitable for use in Astromag experiments: multiwire proportional counters (MWPCs) and scintillating optical fiber trajectory (SOFT) detectors. However, the dynamic range in particle charge that can be covered by any particular configuration of these sensors and associated readout electronics is not sufficient to cover all of the planned objectives of the Astromag facility, with charges ranging from 1 through 28. Present experience with these detectors indicates that MWPCs will provide the best performance for low charges, while SOFT detectors are optimal for heavy nuclei ($Z > 6$). Thus the strawman experiments described in Section IV are based on the use of MWPCs for studies of antiprotons and related objectives, and SOFT detectors for heavy isotope investigations. Other detector types will be considered in the early stages of Astromag definition if they can be shown to provide significant advantages. The construction, operation, and performance of these two types of position sensitive detectors are discussed below.

1. Multiwire Proportional Counters (MWPCs)

Figure III-5 shows a schematic cross-section of a typical multiwire proportional counter of a design which has been successfully used as part of a balloon-borne magnetic spectrometer for antiproton studies. Planes of closely spaced wires serve as the anode and cathode bounding a gas volume from which the ionization electrons produced by the passage of a charged particle are collected. These electrons create an avalanche of secondary electron-ion pairs in the very strong electric fields near the anode wires. As the electrons and ions in the resulting charge cloud rapidly separate, signals are induced on the nearest cathode wires in such a manner that the centroid of this induced charge distribution indicates the location of the track with an accuracy considerably better than the spacing between wires.

In the balloon spectrometer, the MWPCs are operated with a gas mixture of argon/isobutane/freon at 1 atm pressure and with a potential difference between anode and cathode of 4 kV. Onboard gas supplies replenish this gas either continuously or periodically. These detectors, having areas of 0.5m x 0.5m, provide spatial resolution of 125 μm, limited by the intrinsic resolution of the delay line readout that is used. This limitation of the chamber resolution can be removed through the use of a system in which the pulse heights on each of the triggered cathode wires are individually digitized and then digitally combined to obtain the centroid. This system should provide spatial resolution of ≤ 50 μm for singly charged particles, and somewhat better for other light nuclei.

The operation of MWPCs at approximately atmospheric pressure in space requires a vessel to contain the gas. By utilizing a single large vessel which contains all of the MWPCs, the material in the pressure vessel walls will not degrade the rigidity resolution through multiple scattering. However, the dense gas used in the counters would, if used to fill the entire pressure vessel, contribute significant scattering. Therefore it is expected that the MWPC planes will have thin windows (typically 25 μm of mylar), and the space between planes will be filled with helium gas to minimize scattering while balancing the pressure across the thin windows. In such an arrangement, the amount of extra mass which is added if more than one MWPC is included at the same location in the spectrometer is not excessive, since no additional solid windows are needed. This allows the possibility of improving position resolution by combining redundant coordinate measurements.

This approach is used in the strawman instrument described in Section IV.A for measurements of antiprotons and related objectives (see Figure IV-1). In that spectrometer, five position sensing planes are used, with the central plane and the two outermost planes (1.7 m above and below the center plane) each consisting of two dual-coordinate MWPCs, while the intermediate planes (0.85 m above and below the center plane) each consist of a single dual-coordinate MWPC. The vertical spacing of the planes represents a compromise between the best resolution (which requires 4 planes in the middle and two planes each at the top and bottom), and best spurious track rejection (which requires uniform distribution from top to bottom).

2. Scintillating Optical Fiber Trajectory (SOFT) Detectors

The SOFT detectors are illustrated in Figure III-6. These detectors are constructed of optical fibers having a core of polystyrene-based plastic scintillator and a thin acrylic cladding of lower refractive index. The plastic scintillator emits light when traversed by a charged particle and a portion of the scintillation light is transported down the fiber by total internal reflection. Coordinate measurements are made using planes of adjacent parallel fibers (see Figure III-6). These fiber arrays are constructed from square 100 μm x 100 μm single fibers which have been formed into ribbons and mounted on a thin mylar substrate with adhesive. The light output from the ends of the fiber ribbons is viewed through fiber optic couplers by an image intensifier and a video CCD array.

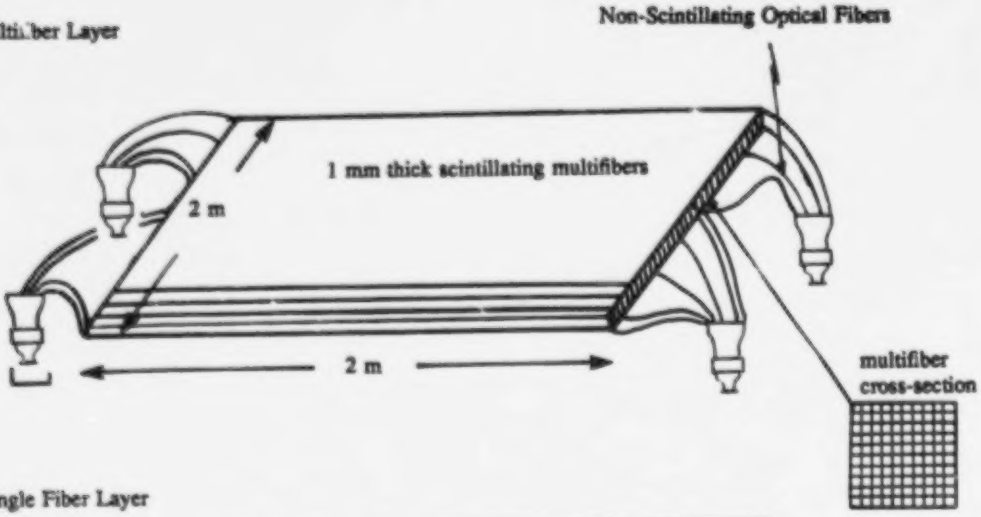
In order to make the trajectory measurements required for the studies of heavy isotopes, a trajectory system consisting of five position sensing planes is envisioned (see Figure IV-3). An x-y position sensing detector (consisting of two SOFT detector layers) at the mid-plane of the spectrometer, together with x-y position sensing detectors 1.7 m above and 1.7 m below this plane, provide the minimum trajectory information required. Additional single planes measuring the coordinate in the direction of maximum magnetic deflection are located 0.85 m above and below the mid-plane to provide the redundancy needed for background rejection without introducing a large amount of mass in which scattering could occur. However, since scatterings in the top and bottom position sensing detectors do not degrade the rigidity resolution, these will be made of multifiber layers with a thickness of 1 mm for each of the single coordinate measurements. These multifibers will provide vectors giving coarse trajectory direction in the entry and exit planes, thus providing additional redundancy.

3. General Considerations

Figure III-7 shows the integral distribution of maximum detectable rigidities expected when two strawman experiments (see Figures IV-1 and IV-3) employing a HEAO-type magnet are exposed to the isotropic cosmic ray flux. This performance, based on an assumed resolution of 50 μm in the position sensing detectors, is suitable for measuring antiproton spectra up to hundreds of GeV, for resolving heavy isotopes up to approximately 10 Gev/amu, and for addressing a wide range of other astrophysical objectives.

The actual realization of position resolution of 50 μm or better over a 1-2 m^2 area for a period of more than a year requires not only detectors with excellent intrinsic spatial resolution, but also the means to control or calibrate systematic effects which could degrade the trajectory measurements. Among the important effects to be considered is the dimensional stability of the trajectory systems since shifts in the detector locations (due, for example, to temperature variation) by even 50 μm will contribute significantly to the rigidity uncertainty. These effects can be minimized by thermal control of the trajectory system (to provide a fixed, uniform temperature within a few degrees centrigrade) and by use of kinematic mounts for the detectors. The trajectory systems will be calibrated on the ground using accelerator beams and electronic methods (such as stimulation by precisely located light sources) to produce a map which relates measured signals to absolute positions in the detector. This map must be accurate to the resolution limit of the position

(a) Multifiber Layer


Non-Scintillating Optical Fibers
1 mm thick scintillating multifibers
2 m
2 m
multifiber
cross-section

(b) Single Fiber Layer

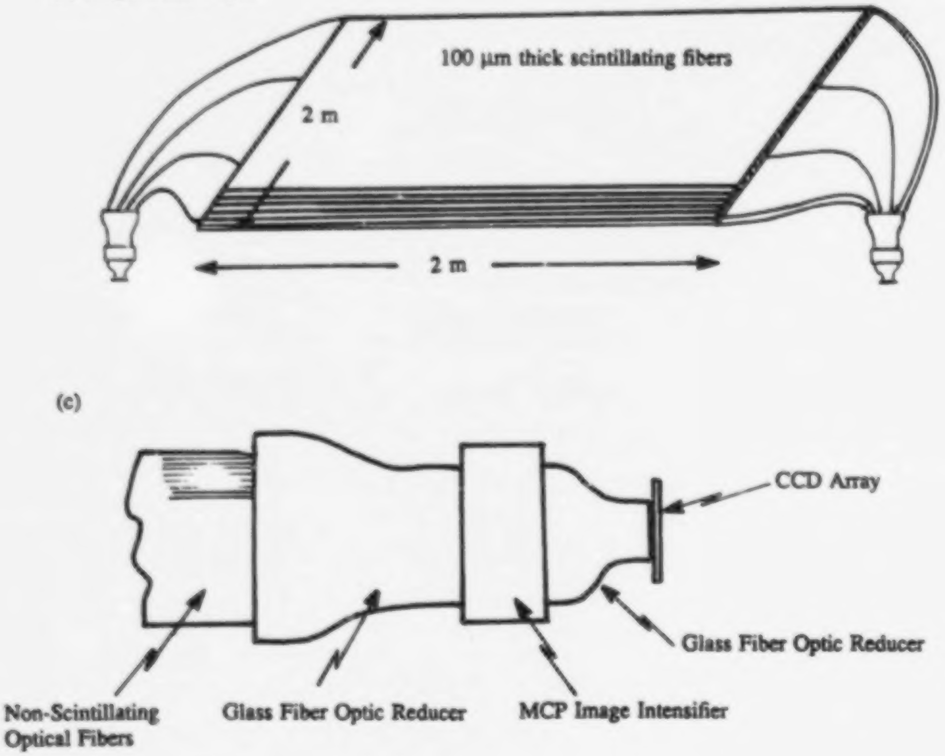

100 µm thick scintillating fibers
2 m
2 m
(c)
CCD Array
Glass Fiber Optic Reducer
Non-Scintillating
Optical Fibers
Glass Fiber Optic Reducer
MCP Image Intensifier

Figure III-6: Details of SOFT detector construction and operation.

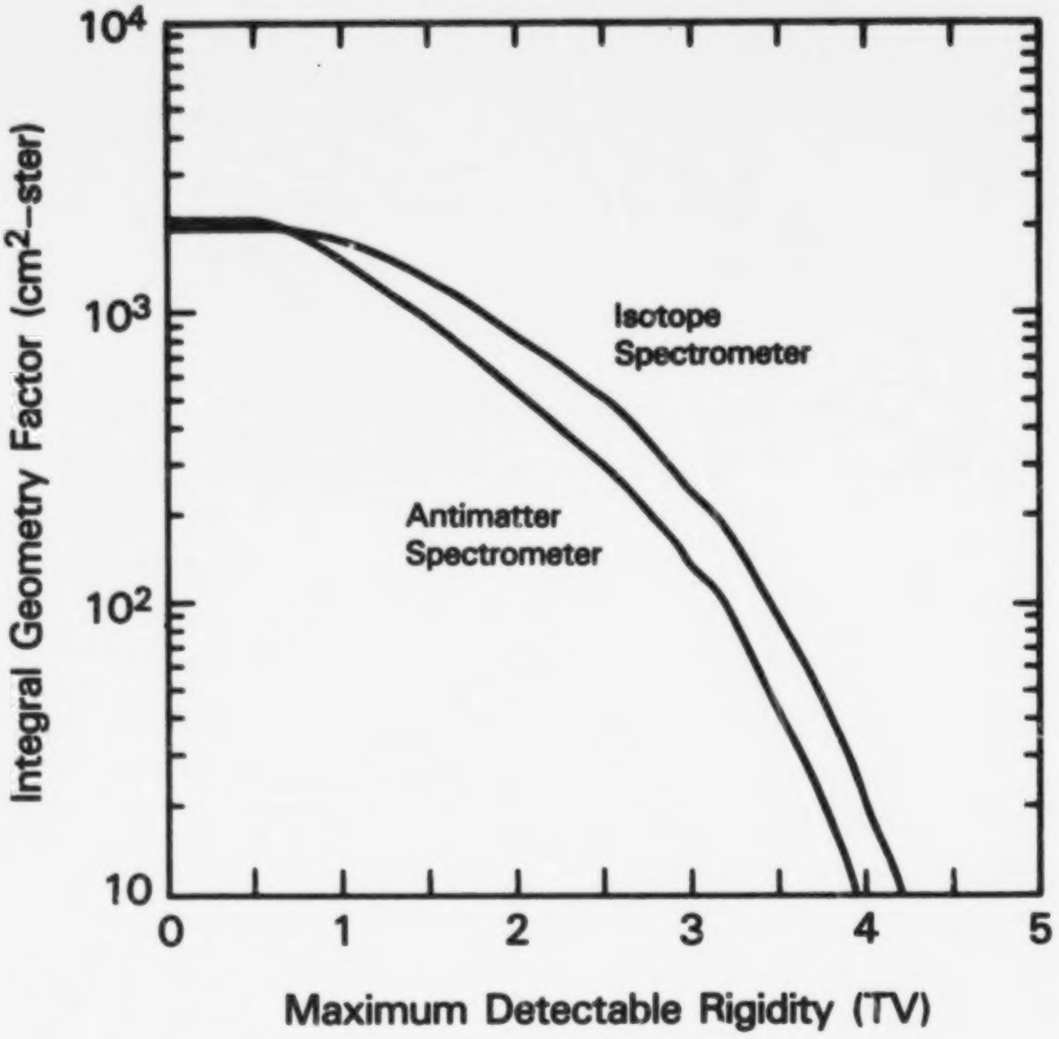


Figure III-7: Integral distribution of maximum detectable momenta.

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sensing detectors and cover the entire detector area. Changes in this response will be monitored on-orbit using the straight tracks of particles collected periodically with the magnet discharged. In addition, the positioning of the trajectory system relative to the magnetic field will be monitored using mechanical, optical, and magnetic field sensors mounted at a number of positions on the trajectory detectors, so that corrections can be made for movements relative to the field.

The strength of the magnetic field is greatest immediately adjacent to the coils and decreases rapidly with distance from the coil. Since the most ambitious objectives of Astromag benefit from increases in the maximum field integral in the spectrometer, it is important to locate the active area of the trajectory detectors as close as possible to the coil face. In addition to minimizing the dewar thickness in this region, the amount of inactive material used for supporting the position sensing detector planes should be reduced as much as possible. Calculations of the spectrometer performance have conservatively assumed a total of 20 cm inactive material in the dewar plus the support structure for the position sensing detector planes. Future studies will determine how much this thickness can be reduced.

The 50 μm position resolution assumed for the Astromag trajectory detectors is not limited by the intrinsic resolution of the sensors. This figure has been used for evaluating the scientific objectives which can be addressed without major new technological advances. However, preliminary tests indicate that significantly better spatial resolution may be attainable --perhaps approaching 25 μm. Detector development work will be continuing and this improved resolution, if achieved, will further enhance the scientific return from Astromag experiments.

The position detectors will be capable of identifying events involving multiple particles, provided that the tracks are separated by a few millimeters or more. This identification is important for eliminating background in most of the envisioned experiments.

The amount of data that could, in principle, be obtained from a single position sensing detector plane at one time exceeds 10^4 bits. However, for a good event at most a small fraction of these bits contain useful information. Onboard data processing will be used to reduce the position information to this essential content and limit the bit rate transmitted to the ground. Data compression is particularly important for low-Z experiments, where event rates will be very high.

D. DATA SYSTEM

The onboard data system will provide a variety of services essential to the operation of the Astromag facility and associated experiments. It will handle all of the data and command traffic between the experiments and the Space Station or Space Shuttle. However, because of the high data rates associated with some of the experiments, custom front-end processing will be an integral part of these experiments, with the facility receiving the data only after some selection and compression has been performed. Figure III-8 is a block diagram of the type of architecture that is envisioned.

The data system will provide the control and monitoring functions required for payload integration on the Space Shuttle and installation on the Space Station. It will, under the supervision of astronauts or ground personnel, control the charging and discharging of the magnet and provide the required monitoring of the status of the magnet and dewar. The data system will also be involved in the alignment and calibration of the trajectory detectors.

Essential features of the data system are a standardized interface and adaptable processing capabilities that will facilitate the replacement of first generation experiments with subsequent generations of instrumentation which will not yet be well defined when the basic data system is being developed.

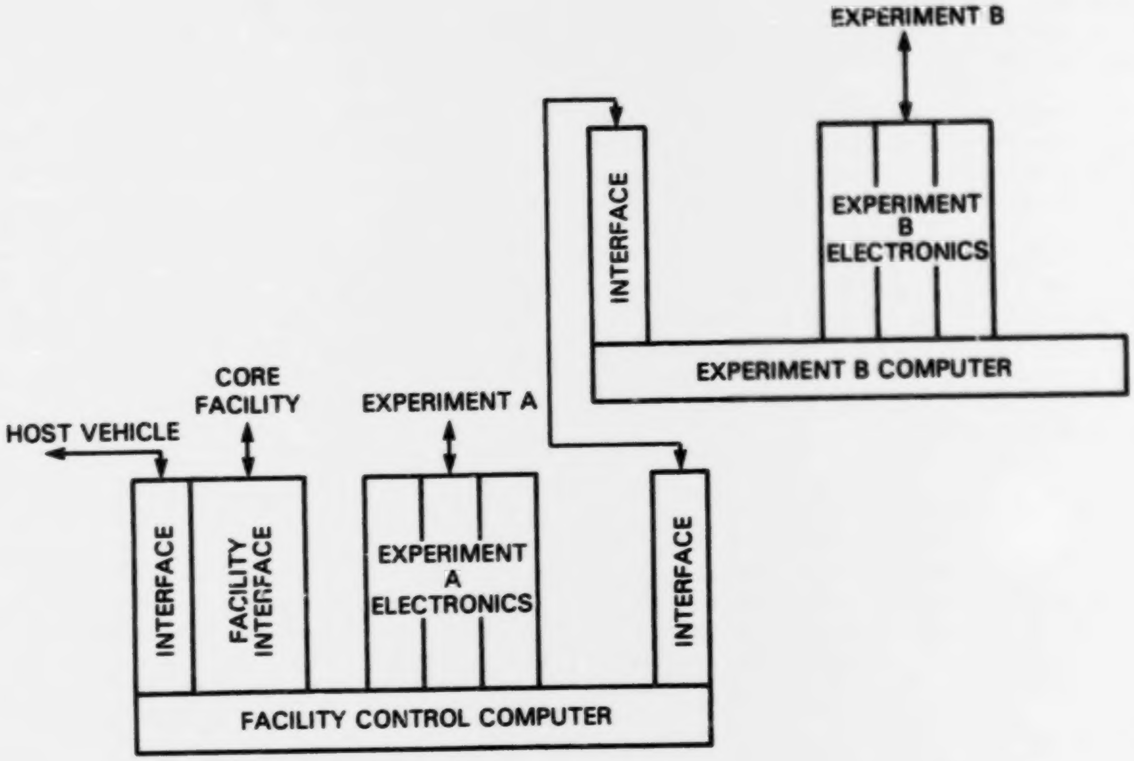
EXPERIMENT B
INTERFACE
EXPERIMENT
B
ELECTRONICS
EXPERIMENT B COMPUTER
CORE
FACILITY
EXPERIMENT A
HOST VEHICLE
INTERFACE
FACILITY
INTERFACE
EXPERIMENT
A
ELECTRONICS
INTERFACE
FACILITY CONTROL COMPUTER

Figure III-8: Onboard data system architecture. Modular construction is used to allow a flexible configuration. Experiments can be accommodated either directly in the facility control computer, or in a dedicated secondary computer. Provisions are made for a variety of host interfaces.

IV. EXPERIMENT CONFIGURATIONS

In the course of this study, several experiment configurations were considered that could address the scientific objectives summarized in Section II. Two instrument configurations described below have been selected as "strawman" instruments for the initial operation of Astromag, under the assumption that one of these would be located at each end of the magnet. After a 1 to 2 year exposure, it is envisioned that the original instrumentation would be replaced by new experiments. Section B describes some of the possible follow-on experiments that could be conducted with this facility. In addition, the Astromag team considered the scientific benefits of a possible high-latitude STS flight of the Astromag magnet, and Section C describes three types of experiments that are especially suited for high-latitude observations.

A. INITIAL INSTRUMENTATION

The Matter-Antimatter Spectrometer and the Cosmic Ray Isotope Spectrometer described below represent two strawman instruments for the initial configuration of the Astromag facility. Table IV-1 summarizes the projected capabilities of these two high-resolution spectrometers. Both instruments are compatible with the proposed design for the core facility, and they would both accomplish significant astrophysical objectives with only modest extensions of existing detector technology.

1. A Matter-Antimatter Spectrometer for Electrons, Positrons, Antiprotons, and Antinuclei

With a measurement of the deflection that a charged particle undergoes in traversing a magnetic field, and knowledge of its direction, it is possible to determine both the sign of the charge of the particle and its magnetic rigidity. As a result, a magnet spectrometer makes it possible to separate electrons from positrons and protons from antiprotons over a wide energy range, providing measurements that can address a number of outstanding questions in particle astrophysics. As discussed below, with Astromag it will be possible to accomplish these objectives simultaneously with a single configuration of ancillary detectors. In addition, this configuration will permit a very sensitive search for light anti-nuclei (such as anti-helium), and it can be used to identify high-energy gamma rays. This section summarizes the detector requirements to accomplish these multiple objectives, and it discusses a strawman instrument configuration that is based on state-of-the-art techniques that have been proven in balloon-flight and/or in accelerator experiments.

Particle Fluxes and Energy Ranges - Required Capabilities: Table IV-2 gives an estimate of the integral fluxes of various singly-charged particles with energies >10 GeV for an 0.1 m^2sr year exposure. The few available measurements of cosmic ray antiprotons indicate a flux considerably greater than expected from production by cosmic ray collisions with interstellar material. In order to determine conclusively whether there is a cosmological contribution to the antiproton flux, and in order to choose among possible models for the galactic propagation of high-energy nuclei which produce secondary antiprotons in interstellar nuclear collisions, it will be necessary to measure the spectrum of cosmic ray antiprotons up to at least several hundred GeV. (See Section II for more detail.)

TABLE IV-1

Summary of Strawman Instrumentation

The Table below summarizes the projected capabilities of the two strawman experiments for the initial Space Station operation.

Matter-Antimatter Spectrometer

Particle Species	Nominal Energy Range (GeV or GeV/amu)
Protons	~ 4 to 5,000
Antiprotons	~ 4 to 1,000
Electrons	~ 5 to 1,000
Positrons	~ 5 to 500
Nuclei $2 \le Z \le 10$	~ 2 to 500
Anti-nuclei $2 \le Z \le 10$	≥ 2
γ-rays	~ 1 to 100

Geometry Factor: $0.1 m^2 sr$
Rigidity Resolution (typical): $\delta R/R \approx R/(4\ TV)$
Effective area for γ-rays: ~ $0.1\ m^2$
Energy Resolution for γ-rays: $\approx 1\%$

Cosmic Ray Isotope Spectrometer

Capability	Element Range	Nominal Energy Range (GeV/amu)
Isotopic Composition	$6 \le Z \le 28$	~ 2 to 6
Elemental Composition	$6 \le Z \le 28$	~ 2 to 1000
Anti-nuclei Search	$6 \le Z \le 28$	≥ 2

Geometry Factor: $0.1\ m^2 sr$
Mass Resolution for Isotopes (typical): $\delta M \approx 0.25$ amu
Charge Resolution: $\delta Z = 0.1$
Rigidity Resolution: $0.05\ m^2 sr$ with $\delta R/R \le R/3TV$.

TABLE IV-2: Approximate Integral Fluxes of Singly-Charged Particles (per 0.1 m²sr year)

Particle	J(> 10 GeV)	J(> 100 GeV)	J(> 1 TeV)
e^-	4×10^6	$2\ 2 \times 10^4$	10^2
e^+ (1)	$2\text{-}6 \times 10^5$	$0.6\text{-}3 \times 10^3$	3-15
p	6×10^8	1.3×10^7	2.6×10^5
$\overline{p}$ (2)	$1\text{-}3 \times 10^5$	$0.7\text{-}6 \times 10^3$	4-100

(1) Lower value is Leaky Box Model prediction; upper value assumes $e^+/(e^+ + e^-) = 0.15$ (see Figure II-4).

(2) Lower value is Leaky Box Model prediction; upper value assumes $\overline{p}/p = 5 \times 10^{-4}$ (see Figure II-1).

Separate measurements of electrons (e^-) and positrons (e^+) are required in the energy range from 10 to 1000 GeV in order to study the effects of radiative energy losses and to deduce the energy spectrum of electrons at the acceleration site. As Figure II-4 indicates, there are presently very few separate measurements of these species beyond 10 GeV.

Thus, a detector system capable of measuring antiprotons to ~ 500 GeV and electrons and positrons to ~ 1000 GeV (i.e., requiring a magnet spectrometer with $R_{max} = 5$ TV) seems to be both necessary and sufficient. To obtain statistically meaningful measurements during an exposure of 1 year duration, a geometry factor of at least 0.1 m²sr is required. One detector configuration that meets these requirements is indicated in Figure IV-1.

In order to separately identify the various singly-charged particles, light nuclei, as well as neutral particles such as γ-rays and neutrons, a combination of detectors is required. In addition to the magnet and trajectory devices, this instrument includes trigger detectors, two transition radiation detectors (TRDs) with their associated proportional counters, and a shower counter located below the other detectors. Incoming particles must first traverse a trigger detector that measures their charge, a function best accomplished with plastic scintillators which measure ionization energy loss. This charge module will also be used for a time-of-flight measurement (in conjunction, with scintillators at the bottom of the instrument, for instance those located in the shower counter) in order to identify downward moving particles. The time-of-flight measurement is very useful to reject background caused by back-scatter from the lower part of the instrument, and it is essential for the detection of antiprotons (see below). The trajectory devices for this spectrometer are multi-wire proportional counters. The ability of this configuration to identify the various species of interest is outlined below.

Measurement of Positrons and Electrons: A detector for cosmic ray electrons and positrons must be very efficient at discriminating against events generated by the much larger flux of protons, a requirement that has been a major obstacle in many previous experiments. The magnetic spectrometer of Astromag will greatly improve the situation by providing clean discrimination between positive protons and negative electrons, but to distinguish between positrons and protons, additional detectors will be required. Suitable devices include shower detectors, transition radiation detectors, gas Cherenkov counters (for a limited energy region), or detectors which tag electrons and positrons by the presence of bremsstrahlung or synchrotron radiation photons.

The detector configuration shown in Figure IV-1 includes a shower counter capable of measuring the energy of electromagnetic cascades with 3% energy resolution $\delta E/E$ at 100 GeV. This energy resolution is roughly comparable to the momentum resolution of the magnet spectrometer, but it improves with increasing energy ($\delta E/E \propto E^{-0.5}$). By requiring that the measurements of momentum and of shower energy are consistent it is possible to reject most proton induced showers, for which a substantial fraction of the shower energy typically escapes. To absorb the energy of electromagnetic showers over the energy range of interest, it is desirable to have frequent sampling of the longitudinal shower profile with a shower counter that is at least 15-20 radiation lengths deep, a requirement that must be balanced against the weight of the counter (1 radiation length of lead weighs 65 kg/m^2).

The combination of magnet spectrometer and shower counter will not be sufficient to identify positrons. The most troublesome background in electron/positron detectors is caused by protons interacting in the detector and producing showers that are indistinguishable from electron showers. For instance, a proton interaction leading to a neutral pion within the first one or two radiation lengths of the shower counter would have this signature. A very effective means to discriminate against such events is provided by transition radiation detectors (TRD's). TRD's will register 5 to 1000 GeV electrons, while protons up to a few TeV will not produce transition radiation.

Figure IV-1 includes two TRD's, located on either side of the magnet spectrometer, which might consist of polyethylene radiators and xenon-proportional chambers successfully used in balloon-borne instrumentation. The discrimination power against protons for a well optimized TRD is of the same order as that of a good shower detector: about 3% acceptance for a proton at a detection efficiency for electrons greater than 95%. Thus, combining the measurements of the shower counter and the two TRDs, the overall discrimination power is about 3×10^4. This estimate does not include the requirement for consistent momentum/energy measurements between the magnet and the shower counter, and this will further increase the discrimination power by perhaps a factor of 10, sufficient for safe identification of positrons.

The instrument described here will be capable of reliably measuring the spectrum of both positrons and electrons up to about 1 TeV. It will also measure the flux of total electrons (negative plus positive) up to a few TeV.

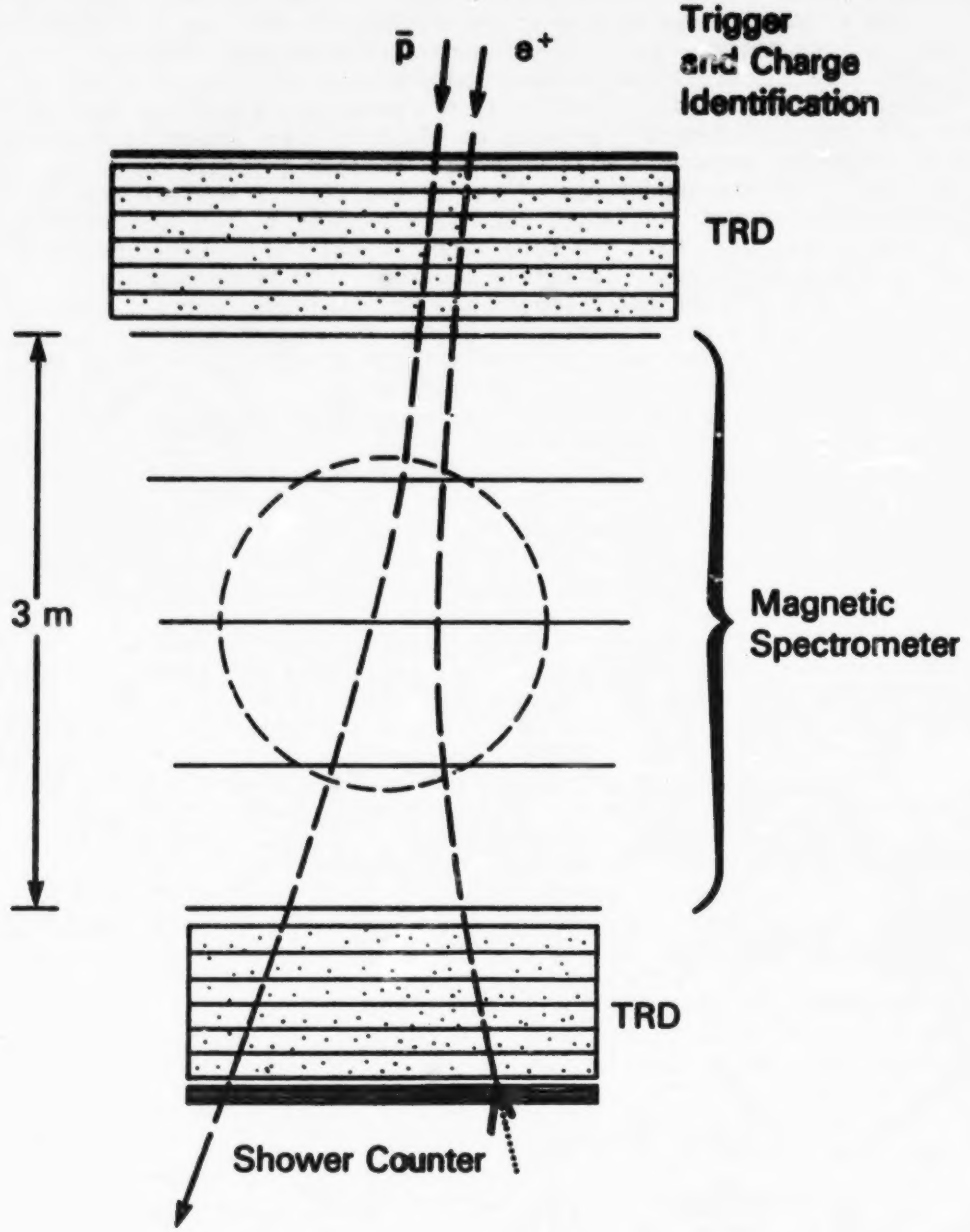
p̄
e⁺
Trigger
and Charge
Identification
TRD
3 m
Magnetic
Spectrometer
TRD
Shower Counter

Figure IV-1: Matter Antimatter Spectrometer: Schematic diagram of detector system designed to measure e^-, e^+, $\bar{p}$, and p over the energy range from ~ 5 to 1000 GeV. Included in the apparatus are two transition radiation detectors (TRD) with associated multiwire proportional counters, an electromagnetic cascade shower detector, and charge identification detectors. Additional scintillators could be added to form an anticoincidence shield for γ-ray studies. High-resolution multiwire proportional counters track particles through the magnetic field.

Measurement of Antiprotons: The main experimental challenge for an antiproton detector is to discriminate between protons and antiprotons on the basis of their opposite deflection in the magnetic field with a discrimination power of ~ 10^5 or better; and to discriminate between electrons and antiprotons with a discrimination power better than 10^2. Protons and antiprotons (with energies < 1 TeV) will not produce a signal in the TRD. Neither will they, in general, produce an electron-like shower in the shower detector. However, about 50% will undergo a nuclear interaction in the shower counter. Note also the importance of the time-of-flight measurement: backwards moving protons (for instance, secondary protons scattered back from the Earth's atmosphere) will have the same path through the magnetic field as downward moving antiprotons. To safely suppress this background, two independent time-of-flight measurements may be required. Protons that undergo large-angle nuclear scattering within the magnet spectrometer can also masquerade as antiprotons. This effect can be minimized if the amount of material in the spectrometer is kept as small as possible. Redundant trajectory detectors are also helpful for recognizing such scatters.

An additional source of systematic background is isolated secondary particles, mainly negative pions, generated in the upper parts of the spectrometer or in surrounding material, that may traverse the spectrometer. For instance, a primary proton interacting in the top TRD can produce a downward moving negatively charged pion. If all other secondary particles escape 'unseen', this event could be mistaken as an antiproton. Fortunately, there are remedies: the amount of material above the magnet spectrometer should be minimized (if necessary, both TRD's could be positioned below the magnet), and the trajectory devices must be capable of recognizing the multiple tracks that are characteristic of high-energy nuclear interactions. Although a quantitative simulation will be required to optimize the detector system in the presence of the variety of possible background effects, it is clear that this detector system can accomplish the objective of separating electrons, positrons, protons, and antiprotons over more than two decades in energy. The expected counting rate for singly charged particles is 10^3 per second. Most of these events will be due to protons. In order that the data transmission rate from this instrument is not too great, onboard data reduction will be necessary.

Measurements of Nuclei and Anti-nuclei: The identification of heavier antiparticles, such as anti-helium, will encounter fewer systematic uncertainties than are found for antiprotons. However, to achieve the statistically possible limit of $\bar{\alpha}/\alpha \leq 10^{-8}$, careful consideration of extremely rare background effects will be necessary. It is expected that large-angle scattering in the magnet spectrometer will be the most significant source of uncertainty. Because of the potential significance of the anti-nuclei search, a second generation experiment to improve on this measurement may be desirable (see Section IV.B).

In addition to the measurements described above, this detector system will also provide extremely precise measurements of the rigidity spectra of individual elements from ~ 5 GV to ~1 TV, corresponding to an energy range from ~4 GeV to ~ 1 TeV for protons and ~ 2 to 500 GeV/amu for other light nuclei with $2 \leq Z \leq 10$.

High-energy Gamma-ray Measurements: Although neither designed nor optimized for this purpose, the experiment configuration shown in Figure IV-1 can also provide a new method for measuring high-energy γ-rays in the $\sim$ 1 to 100 GeV energy region. Addition of an appropriate anticoincidence shield would be required. Then, for example, referring to Figure IV-1, a γ-ray that did not trigger the shield but which converted into an electron/positron pair in the upper TRD and would have the signature of two electrons with opposite curvature traversing the detector at the same time. The role of the magnet spectrometer in this approach is two-fold: to measure the individual energies of the pair, thereby giving a precise measurement of the photon energy; and to ensure that they are of opposite charge, providing important background rejection. Further background discrimination will be provided by the bottom TRD and the shower counter, which will ensure that the pairs observed in the spectrometer are electrons.

It is estimated that the configuration shown in Figure IV-1 could detect γ-rays with approximately 5% efficiency (including pair production only within the upper TRD) with a threshold of about 1 GeV. The threshold comes from the requirement that the members of the pair penetrate the spectrometer without being swept away by the magnetic field. The upper limit on detectable γ-ray energies is about 1 TeV, set by the requirement that the pair undergo sufficient separation, although in practice the instrument is expected to be restricted to lower energies by the available γ-ray flux. The instrument will also be sensitive to high-energy neutrons and γ-rays produced in large solar flares.

Although the collecting power of this particular design is less than that of instrumentation that will fly on the Gamma Ray Observatory (GRO), it should have comparable intrinsic angular resolution, and the estimated count rate from known high-energy γ-ray sources is sufficient to make them detectable at GeV energies. In addition, this instrument should provide greatly improved energy resolution ($\delta E/E \approx 1\%$). A possible approach for a much larger experiment for high-energy γ-ray astronomy is discussed in Section IV.B.

In summary, the Matter-Antimatter Spectrometer described above would permit reliable measurements of the spectra of electrons, positrons, protons and antiprotons over an extended energy range, thereby improving on previous measurements of this kind by 1 to 2 decades in energy and more than a factor of 1000 in collecting power. In addition, it would provide precise measurements of the spectra of light nuclei, search for light anti-nuclei, and detect γ-rays with GeV energies. Such measurements would address a range of fundamental questions in particle astrophysics, questions that also have direct bearing on a broad spectrum of related fields.

2. An Isotope Spectrometer for Cosmic Ray Nuclei with $6 \leq Z \leq 28$.

Among the most exciting of the science objectives that can be addressed by Astromag is the opportunity to extend measurements of heavy cosmic ray isotopes up to energies of several GeV/amu and beyond. This section describes the design of Cosmic Ray Isotope Spectrometer (CRIS), based on existing detector technology, which is capable of providing high-resolution measurements of the isotopic composition of nuclei from carbon ($Z=6$) to nickel ($Z=28$), over the energy range from $\sim$ 2 to 6 GeV/amu. In addition, the experiment can measure the energy spectra of cosmic ray nuclei with unprecedented precision, and it can conduct a sensitive search for heavy anti-nuclei.

A viable isotope experiment must achieve sufficient mass resolution to resolve rare isotopes and must have sufficient collecting power. In the energy region between 2 and 10 GeV/amu the approach that seems to best satisfy both of these requirements combines a measurement of the rigidity (momentum per unit charge) provided by the magnet and associated trajectory devices, with a measurement of the velocity (or momentum per amu, p), provided by a Cherenkov counter. The Cherenkov signal (in units of photoelectrons) can be conveniently expressed as: $L = L_0 Z^2(1 - p_0^2/p^2)$ where L_0 is the number of photoelectrons resulting from $\beta = 1$, $Z = 1$ nuclei and where p_0 is the Cherenkov threshold in momentum/amu. The measured deflection (X) due to the magnetic field can be expressed as $X = (kZ/pA)$, where k (which is approximately proportional to $\int Bxdl$ and depends on the trajectory) can be treated as a constant for the purpose of estimating the resolution. The mass A (in amu) is given by:

$$A = \{\frac{KZ}{Xp_0}\}\{1 - \frac{L}{Z^2 L_0}\}^{1/2}.$$

The energy (or momentum) range over which the magnet-Cherenkov technique can resolve isotopes is governed by the index of refraction of the Cherenkov radiator. At energies far above threshold the velocity resolution is limited by statistical fluctuations in the number of photoelectrons. As an example, for $L_0 = 50$ photoelectrons, the photoelectron contribution to the mass resolution is less than 0.2 amu for $p/p_0 \leq 1.42$. The usable energy range can, however, be extended by including two or more Cherenkov radiators of differing index of refraction, which also provides redundancy.

There are other limitations on the energy range available for isotope studies. On the low-energy side the geomagnetic cutoff in a 28.5 degree inclination orbit does not allow a useful flux of nuclei with energies below 1.5 GeV/amu. At sufficiently high energies, the rigidity resolution of the spectrometer limits the mass resolution. Assuming a rigidity uncertainty $\delta R/R = R/R_{max}$, where R_{max} is the "maximum detectable rigidity", the corresponding uncertainty in mass is given by $\delta A_R = A(R/R_{max})$. R is related to the kinetic energy per amu, T by

$$T = [(\frac{R\ Z\ e}{A})^2 + m_u^2]^{1/2} - m_u$$

where $m_u = 0.931$ GeV, the energy equivalent of 1 amu. Since clean isotope resolution requires $\delta A_R \leq 0.2$ amu, the maximum energy is

$$T_{max} = [(\frac{0.2\ R_{max}\ Z\ e}{A^2})^2 + m_u^2]^{1/2} - m_u.$$

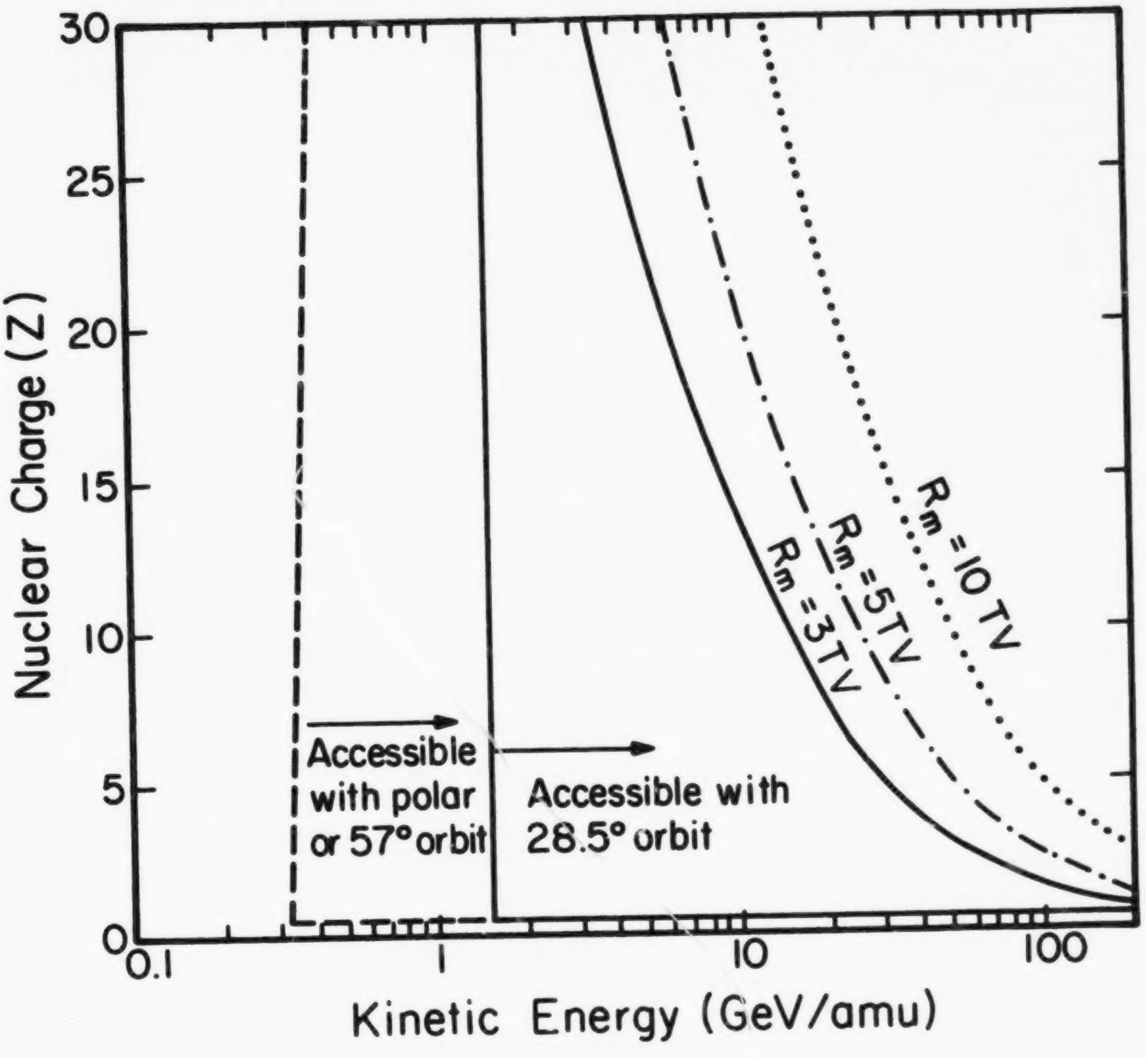

Figure IV-2: Plot of the energy range available for isotope studies of nuclei with nuclear charge $1 \leq Z \leq 28$. The lower energy limit for a 28.5 degree orbit is set by the geomagnetic cutoff, while the lower limit for a high-latitude orbit requires that the nucleus be above threshold in a Cherenkov counter with n=1.5. The upper limits to the energy range are for various values of the maximum detectable rigidity, assuming that the rigidity resolution contributes 0.2 amu to the mass resolution.

TABLE IV-3

Counter Name	Radiator Material	Index of Refraction	Thickness (cm)	Estimated Photoelectrons[a]	Energy Range (GeV/amu)[b]
C1	Aerogel	1.05	10	50	2.1-3.5
C2	"	1.025	10	25	3.3-4.6
C3	"	1.015	12	20	4.5-5.7

[a] From $Z = 1$, $\beta = 1$ particles

[b] For an ^{56}Fe mass resolution of ≤ 0.3 amu

Figure IV-2 shows the energy range available for isotope studies for various assumed values of R_{max}. Note that for $R_{max} = 5$ TV there is a window from about 2 to 6 GeV/amu that is available for studies of all nuclei with $Z \leq 28$.

A straw-man experimental configuration, optimized for isotope studies in the energy range from 2 to 6 GeV/amu, is shown in Figure IV-3. It includes three aerogel Cherenkov counters (C1, C2, and C3) with indices of refraction of $n = 1.05$, 1.025, and 1.015 and corresponding energy thresholds (E_0) at 2.1, 3.3, and 4.5 GeV/amu. Also included are two trigger counters (T1 and T2) which define the geometry and measure the charge of the nucleus before and after it passes through the spectrometer. In this design T1 and T2 are Cherenkov counters with low-threshold radiators such as Pilot-425 ($n = 1.5$; $E_0 = 0.32$ GeV/amu) or Teflon ($n = 1.33$; $E_0 = 0.48$ GeV/amu), for which all allowed nuclei have a nearly saturated response proportional to Z^2. Although the charge identification function of T1 and T2 could in principle be performed by a scintillator such as NaI or plastic scintillator, Cherenkov counters can provide better charge resolution, and would also provide velocity resolution for particles below the C1 threshold.

Table IV-3 summarizes the properties of the aerogel Cherenkov radiators that are assumed for the configuration in Figure IV-3. Aerogel radiators of similar index of refraction were successfully flown in the French/Danish HEAO-3 experiment. Such aerogels can be produced with indices ranging from 1.01 to 1.2; the present choice of indices for C1, C2, and C3 optimizes the yield of events in a 28.5 degree orbit. Each Cherenkov radiator will be surrounded by a highly-reflecting light-integration box viewed by 30 to 40 photomultiplier tubes. Modern high-reflectance paints make it possible to collect a majority of the visible light emitted by the radiator, while wavelength shifting techniques also allow much of the UV light to be collected. In Table IV-3 the energy range covered by each counter corresponds to the interval over which the total mass resolution (including all contributions) is estimated to be < 0.3 amu (see below).

In the configuration shown in Figure IV-3, the detectors below the magnet are located so as to take advantage of the high field region of the magnet. The detector above the spectrometer might be a Cherenkov detector for

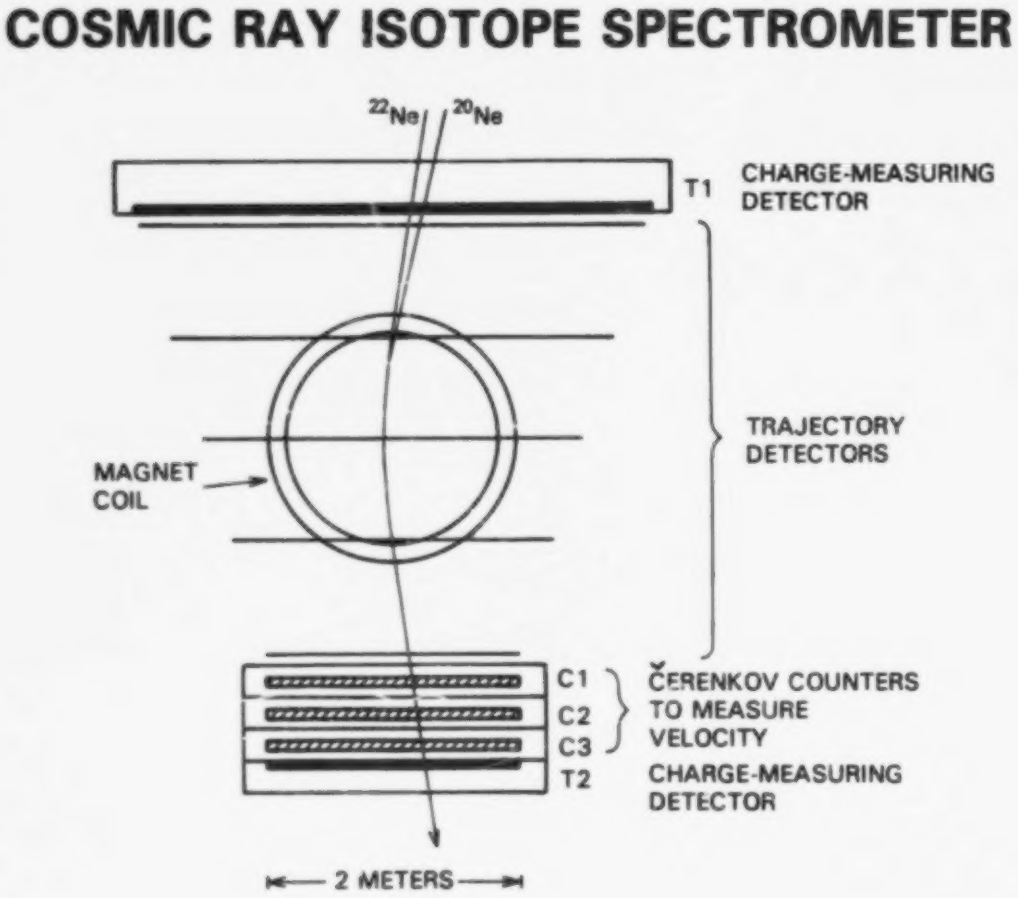
COSMIC RAY ISOTOPE SPECTROMETER
²²Ne
²⁰Ne
T1
CHARGE-MEASURING DETECTOR
TRAJECTORY DETECTORS
MAGNET COIL
C1
C2
C3
T2
ČERENKOV COUNTERS TO MEASURE VELOCITY
CHARGE-MEASURING DETECTOR
2 METERS

Figure IV-3: Cosmic Ray Isotope Spectrometer: Schematic diagram of a cosmic ray isotope spectrometer designed to identify isotopes of cosmic rays using the magnet/Cherenkov method. Included are three Cherenkov radiators (C1, C2, and C3) used to measure velocity, and two charge measuring detectors (T1 and T2). Particle trajectories are determined by scintillating optical fibers arranged in layers.

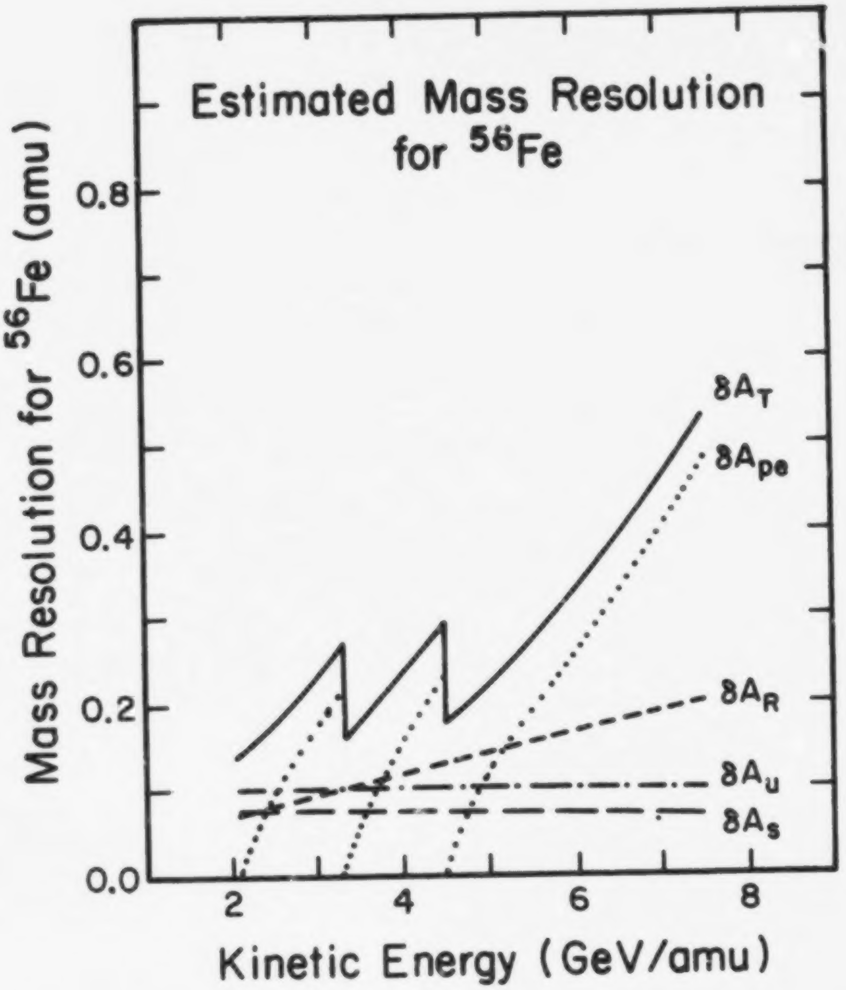

Figure IV-4: Estimated mass resolution (δA_T) for ^{56}Fe nuclei as a function of energy/amu. Estimated contributions due to photoelectron statistics (δA_{pe}), rigidity resolution (δA_R), Cherenkov counter and magnetic field uniformity (δA_u), and multiple scattering (δA_S) are indicated.

determining charge. The trajectory devices are assumed to be composed of the scintillating fibers discussed in Section III. The resulting geometry factor for triggering all counters is ~ of order 0.1 m^2sr. An MDR of ≥ 3 TV is required to resolve the isotopes of the heaviest elements. It is assumed that the dynamic range of the trajectory detectors will not be sufficient to cover the entire range from Z=1 to Z=28, and so the design will be optimized for studies of carbon (Z=6) to nickel (Z=28) isotopes. The Cherenkov counters could also be used for studies of the isotopes of lighter nuclei.

The expected yield of isotope events (with $\delta A \leq 0.3$ amu) ranges from almost 3×10^5 events per year for carbon, to ~ 3×10^4 per year for Si, to about 10^4 for iron nuclei, sufficient to address essentially all of the objectives outlined in Section II. For example, the expected yield of ^{59}Ni events per year is ~ 30 (note that these may actually be observed as ^{59}Co events if the time-delay between nucleosynthesis and cosmic ray acceleration is greater than 10^5 years).

Contributions to the mass resolution of the spectrometer have been evaluated in some detail in order to optimize its design. A reasonable mass resolution goal for isotope experiments is $\delta A \leq 0.25$ amu, sufficient in principle to resolve adjacent isotopes that differ in abundance by 100 to 1. Figure IV-4 shows the expected mass resolution (δA_T) for ^{56}Fe nuclei as a function of energy per amu, based on estimated contributions from several sources. The photoelectron contribution (δA_{pe}) assumes the yields in Table IV-3, which are estimated from recent laboratory, accelerator, and balloon studies of Cherenkov counters. Other contributions are due to multiple scattering in the material composing the trajectory devices (δA_S), and the rigidity resolution of the spectrometer (assuming that position resolution dominates this contribution and that $R_{max} = 3$ TV). These are believed to be the major contributions to the mass resolution, and it is assumed here that all other (unknown) errors combine to contribute 0.1 amu when added in quadrature (δA_U). This requires that the response of the Cherenkov counters be mapped to an accuracy of <0.5% (which should be possible at a heavy-ion accelerator such as that at Brookhaven), and that the field of the magnet be mapped to <0.2%.

Note that when the various contributions are added in quadrature, the resulting mass resolution for heavy isotopes such as ^{56}Fe is <0.3 amu over the energy range from 2.1 to 5.7 GeV/amu, with a typical value of approximately 0.22 amu. The mass resolution will be somewhat better for lighter elements, because of the reduced contributions from δA_R and δA_U.

An important aspect of the design considered here is the redundancy provided by the multiple Cherenkov counters. Note that there are always at least three (and sometimes as many as five) independent measures of the charge (Z), the momentum/amu (p), and therefore the mass (A) of the isotope. Although one of these determinations is always more precise than the others, requiring reasonable agreement between them is a powerful technique for identifying background due to nuclear interactions within the material of the spectrometer, or other rare occurrences such as chance coincidences. Note that the combination of these independent estimates may result in somewhat improved mass resolution over that shown in Figure IV-4.

In addition to its mass resolution capabilities, this detector system can also measure the energy (rigidity) spectra of cosmic ray nuclei with $6 \leq Z \leq 28$ with unprecedented resolution over the energy range from ~ 2 to 500 GeV/amu. It can also (with the addition of a time-of-flight measurement) conduct a very sensitive search for anti-nuclei, detecting, for example, > 10^7 carbon, nitrogen, and oxygen nuclei per year between 1 and 10 GeV/amu.

In summary, the experiment considered here can provide high-resolution observations of a wide range of isotopes in an energy range not previously accessible to direct isotope measurements. The expected yield of events is approximately 2 orders of magnitude greater than presently available from measurements at lower energies. The design suggested is based entirely on existing detector technology, and while detector testing, calibration, and optimization are essential to its success, no new technological break-throughs are required. In view of the broad astrophysical significance of cosmic ray isotope studies, such an experiment promises to make optimum use of the Astromag capabilities.

B. FOLLOW-ON INSTRUMENTATION

The experiments described below have also been identified as being suitable candidates for development and eventual flight with the Astromag facility. Some of these experiments also can be accomplished with existing detector technology, but they address a somewhat more limited range of objectives than the two strawman experiments described above. Other experiments included here will require the development of new instrument capabilities. Although this list of potential experiments is by no means complete, it gives an indication of the wide range of scientific objectives that Astromag can address.

1. A Light Isotope Spectrometer

Isotopic composition measurements are among the prime scientific goals of Astromag. These measurements should cover a wide variety of elemental species, from H (Z=1) to Ni (Z=28), and as broad an interval in energy as possible. This probably requires a larger dynamic range in the detector systems than is feasible with a single set of instrumentation. Therefore, the Cosmic Ray Isotope Spectrometer described in Section IV.A is optimized for measurements of the heavier isotopes ($Z \geq 6$) with energies of several GeV/amu, while in the following the requirements are briefly discussed for a spectrometer for light isotopes ($1 \leq Z \leq 8$) that extends to higher energies.

The lighter isotopes include some of the most interesting species of secondary origin, including ^{2}H and ^{3}He, both of which are produced predominently by spallation of primary ^{4}He nuclei, and the isotopes of the elements Li, Be, and B, which are spallation products of heavier nuclei (mostly C and O). There is a specific interest in extending measurements of these secondary isotopes to very high energies. Measurements of ^{3}He and ^{2}H would provide information on the propagation of ^{4}He, which is needed to complement the data on other secondaries, notably antiprotons and positrons which are produced by primary protons, and the secondary nuclei produced by heavier primary species such as carbon, oxygen, or iron. Of particular interest is the radioactive clock isotope ^{10}Be (half-life 1.6×10^6 years), most of which decays at low energies (< 1 GeV/amu) within the mean-life of cosmic rays in the galaxy (see Figure II-6). Measurements of the abundance of ^{10}Be over a wide energy range--over a wide range of Lorentz time-dilation factors--would provide the opportunity for investigating the distribution of lifetimes and, correspondingly, the distribution of matter traversed by heavy nuclei in the galaxy.

Because these light isotopes are relatively abundant, the required collecting power is somewhat more modest than for heavier nuclei. Above 10 GeV/amu, the expected integral flux of both ^2H and ^3He is several times 10^7 per m^{2}sr year, while that of ^{10}Be is ~ 10^5 per m^{2}sr year. For given velocity and rigidity resolution, a magnet/Cherenkov spectrometer can perform measurements of light isotopes to significantly higher energies than those of heavy isotopes (as shown in Figure IV-2). Thus, an instrument with a geometry factor of ~ 0.1 m^{2}sr and a maximum detectable rigidity, R_{max} ~ 5 TV, could provide measurements up to about 50 GeV/amu for ^{10}Be. The major experimental challenge is then the development of a counter system capable of accurate velocity measurements at high energies. Most promising towards this goal are ring imaging Cherenkov systems (RICS) which are presently under development at several laboratories.

A light isotope spectrometer on Astromag might incorporate the following components:

a) A magnet spectrometer with MDR ~ 5 TV and 0.1 m^{2}sr. Note that the trajectory measuring detectors, for reasons of sensitivity and dynamic range, may have to be different from those used for measurements of heavier nuclei.

b) Detectors to measure nuclear charge (solid ionization or Cherenkov devices).

c) Cherenkov counters that measure velocity in the energy range from 1 to 10 GeV/amu. These could be either high-pressure gas or aerogel counters, similar to those described in Section IV.A.

d) RICS counters for velocity measurements over the range from 10 GeV/amu to 50 GeV/amu.

It appears that an arrangement with RICS devices above, and low-energy Cherenkov systems below the magnet spectrometer might offer an attractive configuration.

2. An Advanced Anti-nuclei Experiment

The Matter/Antimatter Spectrometer described in Section IV.A will detect ~ 10^8 He nuclei per year with energies ≥ 1 GeV/amu, and will, therefore, be in a position to conduct a sensitive search for anti-helium, and also heavier antinuclei. However, this experiment will be optimized to study electrons, positrons, protons, and antiprotons over as broad an energy range as possible, and as a result, it may not be the optimal design required to search for anti-nuclei with maximum sensitivity. Because of the potential significance of anti-nuclei searches, it is desirable to consider a second-generation anti-nuclei experiment that could provide significantly improved sensitivity, and that might at the same time address other important objectives. It appears that a study of light isotopes ($1 \le Z \le 8$) in the ~ 2 to 10 GeV/amu energy range might be compatible with this objective.

In order to take advantage of the facility nature of Astromag this advanced anti-nuclei experiment could be a follow up to the Matter/Antimatter Spectrometer, quite possibly making use of the same trajectory and time-of-flight instrumentation, but substituting other ancillary detectors for the shower counter and transition radiation detectors (see Section IV.A and Figure IV-1). This substitution could result in an increased geometry factor and correspondingly greater yield. The possibility of reusing the trajectory detectors should be taken into account in the design so that no artificial constraints are built in unknowingly.

Note that significant antiproton measurements can be carried out by suppressing the proton background by a factor of ~ 10^5, while the rejection called for by the anti-helium study is a factor of ~ 10^9 or more. The primary source of such background is expected to be nuclear scattering, which might enable an ordinary helium nucleus to mimic the deflection of an anti-helium. One key to reducing this background is to provide for redundant measurements of the particle's energy or velocity (such as might be provided by a Cherenkov counter), which would then be required to be consistent with the measured rigidity. In this way the vast majority of scattered particles can be eliminated. A second possible means of reducing background is to add additional trajectory devices.

In order to maximize the number of cosmic ray helium nuclei available for study, this experiment is best conducted in the energy range from ~ 1 to 10 GeV/amu, which includes ~ 75% of the integral He flux available in a 28.5 degree orbit, giving a total of ~ 10^8 He that could be collected in a year. In this energy range both aerogel and gas Cherenkov counters can operate, as well as other possible velocity measuring techniques. Thus, one attractive possibility would be to combine the anti-helium search with a the light isotope spectrometer described in the previous section. Indeed, there is no reason why the same Cherenkov detectors used to study heavy isotopes could not be reused for this study, merely by providing for somewhat greater signal amplification. In this case there are several possibilities, including the transfer of these counters to the low-Z end of the magnet, or a replacement of the trajectory devices used for the heavy isotope experiment.

In summary, it appears that a study of light isotopes and a sensitive search for anti-nuclei in the 1 to 10 GeV/amu energy range might well represent compatible objectives, and that such an experiment might be able to make optimum use of the facility nature of Astromag through the re-use of existing instrumentation.

3. Exotic Particle Searches and High Energy Interactions

The combination of a high magnetic field and large collecting area that is available with Astromag can provide a new capability to search for hypothetical exotic particles that may be present in the cosmic radiation but do not survive to ground level. For example, a possible second-generation Astromag experiment which could carry out searches for strange-quark matter ("nuggets") and study high energy nuclear interactions is shown in Figure IV-5. In this design, detectors that determine the trajectory and charge, Z, of the primary particle are followed by a thin interaction target plate (~ 1/20 nuclear mean-free path) and a decay and drift region in which strange particles may decay. This space also allows particles to separate so that their tracks can be individually followed. Trajectory detectors before and after (and possibly inside) the magnetic field region measure the secondary particle momenta and the sign of their electric charge. Next, the Pb plates

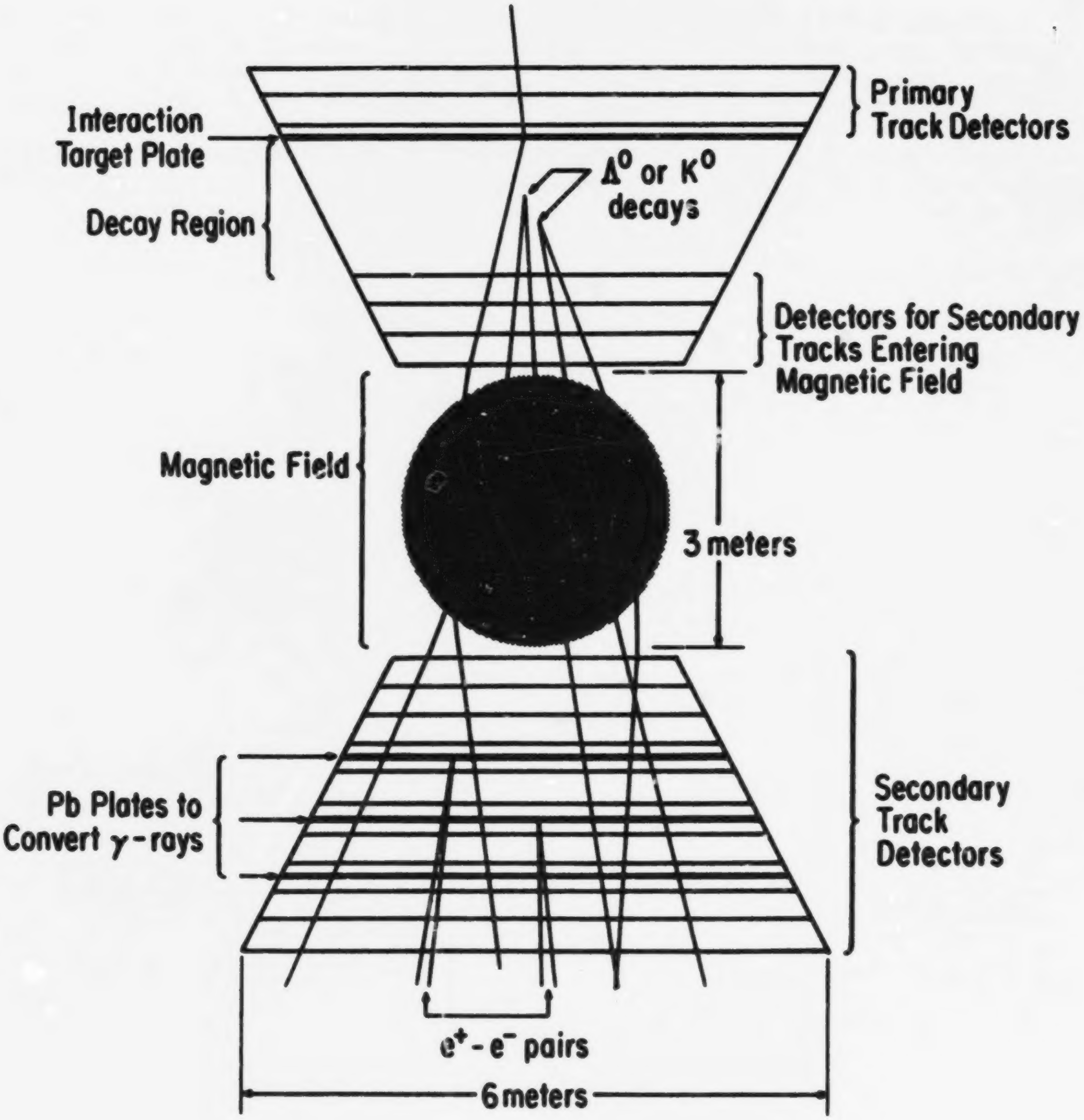
Primary
Track Detectors
Interaction
Target Plate
Λ^0 or K^0
decays
Decay Region
Detectors for Secondary
Tracks Entering
Magnetic Field
Magnetic Field
3 meters
Pb Plates to
Convert γ-rays
Secondary
Track
Detectors
e^+-e^- pairs
6 meters

Figure IV-5: Cross-section of a detector system designed to search for strange-quark matter and other exotic particles and to study nuclear interactions. A hypothetical event with two strange particle decays ($\Lambda^0 \rightarrow p + \pi^-$ and $K^0 \rightarrow \pi^+ + \pi^-$) and two γ-rays is shown.

(~ 1 radiation length) are each followed by trajectory measuring detectors in order to observe γ-ray conversions.

Strange-quark matter would be recognized by the large fraction of strange particles among the secondaries, especially by the presence of two or more strange baryons, which would be unlikely from collisions induced by normal nuclei. Based upon an extrapolation from the "Centauro" event, and a 1 m^2sr geometry factor, several hundred events might be observed in a year with energies exceeding 10 GeV. Estimates of the flux of H-dibaryons, the lightest quark-matter isotope which might be stable, from a point source such as Cygnus X-3 suggest that hundreds of such events might be observed with energies above 1 GeV in a year, without controlling the orientation the experiment to point at a specific source.

4. Large Area Detector for High Energy Gamma Rays

Over the next few years the Gamma Ray Observatory (GRO) will extend studies of cosmic γ-rays up to 10 or 20 GeV for the brightest sources, while ground based observations of these sources at higher energy may well extend down to ~100 GeV with an angular resolution limited to about 1 degree. It appears, however, that an unexplored gap in the γ-ray spectrum will remain between 10 and 100 GeV. It will be extremely important to bridge this gap--to tie observations of the very high energy sources observed in ground-based studies to observations at much lower energies. The design goals for such a detector are that it have an energy range that extends to at least 100 GeV, that it improve significantly on the high-energy sensitivity of previous instrumentation, and that it offer improved angular resolution. One possible design for such an instrument that could be located in the Astromag fringe field is discussed below.

A high energy γ-ray detector must measure both the energy and the arrival direction of the photons. When γ-rays with >100 MeV interact with matter, by far the most probable result is the production of an electron/positron pair. The superconducting magnet makes it possible to measure the γ-ray energy by observing simultaneously the bending of the electron and positron in the magnetic field. After conversion, the magnetic field will separate the pair so that their individual rigidities can be determined to high precision. The magnetic spectrometer replaces the calorimeter used in conventional γ-ray spectrometers. The radiative corrections are such that any line feature in the spectrum could be detected with better than 1% resolution, and photons which have their energies underestimated are always "lost" among the more abundant lower energy photons. The angular resolution of any detector that relies on pair production is limited by the nuclear-recoil momentum transfer in the pair conversion process and by multiple scattering in the target converter. Since both processes vary inversely as the momentum, the uncertainty in the angular area on the sky varies inversely as the square of the energy. Integrating over the incident γ-ray spectrum, it can be shown that as long as the source photon spectrum is harder than E^{-3}, the source location accuracy will improve (decrease) with increasing energy.

The field strength required for this method is less than that needed for the Matter/Antimatter and Cosmic Ray Isotope Spectrometers, so a large-area γ-ray detector of area ~ $4m^2$ could be located in the fringe field of Astromag and still have sufficient bending power. Assuming a converter 0.4 radiation lengths thick, detector modules could be built which would have an effective area of ~ 1 m². There are actually four separate regions of sufficient field strength in the dual opposed coil (or HEAO) magnet configuration, so a total area of ~ 16 m² (~4m² effective area) might be achieved. With such a counter, all of the COS-B γ-ray sources would be detectable above 1 GeV, giving $\geq 10^3$ counts per 2 weeks exposure, and a source resolution of better than an arc minute.

It might be desirable to view portions of the sky (e.g., the galactic plane) for long periods of time with high precision to obtain deep surveys at γ-ray energies above 1 GeV. If four detectors, each with a field of view of 60 degrees, were tilted to cover different areas of the observable sky, about 25% of the accessible sky could be viewed at all times. The disadvantage of the technique is its inability to point, and its limited energy range. This instrument might be utilized in conjunction with a smaller pointed telescope optimized to study 0.03 to 1 GeV photons which could be located elsewhere on the Space Station.

In summary, Astromag might provide some advantages for identifying high energy γ-rays and for localizing point sources with high precision. By measuring the photon spectra from 1 to 100 GeV where π° decay γ-rays dominate, it would be capable of mapping the nucleonic component of cosmic rays in the galaxy and localizing their sources. It would help in determining whether those sources are producing hard spectra as would be expected from cosmic ray shock acceleration models, and it would provide a means of localizing, perhaps for the first time, the sites where the acceleration of cosmic ray nuclei is taking place. For a large-area detector such as this the use of a magnetic field offers an attractive new method of identifying photons and measuring their energy.

C. HIGH LATITUDE STS STUDIES WITH ASTROMAG

One option that should be considered during the development of Astromag is the possibility of an STS flight that might include a prototype or scaled-down version of one of the experiments under development or consideration for the Space Station Facility. If flown in a high-inclination (>57 degree) orbit, such a flight would make it possible to perform important observations over a rigidity range (less than about 5 GV) that is inaccessible to Space Station instrumentation because of the geomagnetic cutoff. Thus, in addition to performing important tests of detector and engineering systems, a high-latitude STS flight would provide important new data that would complement that obtained at higher energy from the Space Station facility. A brief summary of the expected benefit of high-latitude STS studies in three experimental areas appears below.

1. Antiprotons at High Latitude

A high latitude mission of Astromag on the STS would make it possible to explore the antiproton spectrum and search for antinuclei in an energy range inaccessible to the Space Station. Studies in this energy range, from 0.3 to 5 GeV are especially important to an understanding of whether cosmic ray collisions with the interstellar gas can account for the observed antiproton spectrum, since models of this process predict a significant decrease in the antiproton flux below ~ 2 GeV as a result of the kinematics of antiproton production (see Figure II-1). There are also other, more exotic models for producing cosmic ray antiprotons that predict structure in the antiproton spectrum in this energy range (e.g., Figure II-2).

Although there are presently no observations available of cosmic ray antiprotons from 0.3 to ~ 2 GeV, preliminary observations in this energy range will become available over the next few years from balloon-borne experiments. However, depending on the actual magnitude of the observed antiproton flux, balloon observations may well be limited by the contribution of antiprotons produced in collisions of cosmic rays with the atmosphere. In any case, a high-latitude STS flight of Astromag would have perhaps 10 times the collecting power of a typical balloon experiment, and it would therefore provide valuable observations in a very interesting energy range.

2. Electrons and Positrons

In the energy range from 20 MeV to 2 GeV for positrons and 20 MeV to 400 MeV for electrons, the atmospheric background is so dominant that reliable flux measurements are very difficult to obtain from balloon-borne experiments. With a magnet spectrometer in a high-latitude orbit these data would be straightforward to obtain and would be of great importance in the investigation of several phenomena. For many years it was thought that the primary use for positron measurements would be to study solar modulation. It was assumed that the interstellar positron spectrum could be calculated from the measured proton spectrum and the deduced interstellar matter density. Recent measurements which indicate an excess of antiprotons are at variance with this classical picture. Positrons must now be viewed as a critical cross check on the conclusions drawn from the antiproton measurements to be obtained with Astromag.

The electron spectrum also assumes a new importance since it can, in principle, be measured in interstellar space by detecting the synchrotron radiation produced as electrons spiral in the galactic magnetic field. Electrons also interact with interstellar matter to produce gamma-rays which will be studied in detail by GRO. In addition, such measurements would provide a test of solar modulation models that depend on the sign of the particle's charge, a subject of considerable recent interest. As a result, a high precision determination of both the electron and positron spectra below ~ 5 GV would have far reaching implications for some of the basic questions which the Astromag facility is designed to answer.

3. Studies of Cosmic Ray Isotopes on a High-Latitude STS Flight

An STS flight of Astromag in a high-inclination orbit could provide important new observations of cosmic ray isotopes that would complement studies planned at higher energies with the Space Station facility. For example, using the magnet/Cherenkov method discussed in Section IV.A with higher-index radiators (or possibly another approach), a magnet spectrometer flown in either a 57 degree or polar orbit could resolve isotopes with ~ 0.4 to ~ 2 GeV/amu, an energy range that is inaccessible to Space Station studies because of the geomagnetic cutoff (see Figure IV-2). Although this energy range can be studied by balloon-borne instrumentation, an STS flight of Astromag would have the advantage of being above the atmosphere, and it would provide an important test of detector and engineering systems (and possibly also the detection method) planned for the Space Station facility.

An STS isotope spectrometer might be directed towards either light (perhaps $1 \leq Z \leq 10$) or heavier (perhaps $6 \leq Z \leq 28$) isotopes. For comparison purposes, we assume an effective geometry factor of 0.1 m^2sr, which would result in ~ 10^5 C events and ~ 10^4 Si events between about 0.4 and 2 GeV/amu over a 5-day flight at 57 degrees or greater. Because of the increased flux at lower energies, this yield is ~ 10% of that expected per year at >2 GeV/amu from an experiment on the Space Station facility. Such a flight would address a number of the objectives discussed in Section II, including an important extension of the range of time-dilation factors over which radioactive clocks could be studied.

D. OPERATION OF COMPLETE MAGNET SPECTROMETER AT GROUND LEVEL

In addition to carrying out accelerator calibration of the magnet and experiments, it may be advantageous, if the schedule permits, to operate the system at ground level, or preferably at mountain altitude, prior to launch. Although the individual components can be tested separately, problems of integration and interference require that the complete instrument be assembled and operated. Procedures for adjusting operating thresholds and voltages can be tested, as well as suggested responses to malfunctions of particular components when in space. Measurements of known cosmic ray parameters such as the momentum spectrum and charge ratio of muons can be used to check that the instrument is attaining its specified rigidity resolution. The ability of the system to identify e^+, e^-, $\bar{p}$, p and deuterons, and to reject potential spurious background events can be studied.

Measurements can be made which will have comtemporary scientific merit. These include the spectra of antiprotons, protons, and deuterons in the atmosphere. The antiproton flux can be compared with the predictions available for secondary production. These predictions bear a direct relation to the production of antiprotons in interstellar space, providing an important cross check on the underlying cross sections and calculations needed for an understanding of the primary antiproton spectrum. Deuteron spectra in the atmosphere are poorly known, and would provide a check of the calculations for deuteron production in interstellar space. It is envisaged that a small number of Ph.D. programs could reach fruition based upon ground-level observations of a month's duration.

V: INTERFACES TO STS AND SPACE STATION

The Astromag is a large aperture superconducting magnet spectrometer facility for fundamental investigations in particle astrophysics. It is envisioned to be a long-lived facility on the space station where a variety of experiments can be performed. The detector complement on Astromag will be periodically reconfigured and the magnet resupplied with cryogenic fluid. One possible mounting configuration for Astromag is shown in Figure V-1. Astromag would be at the end of a structural outrigger, housed within an environmental enclosure for thermal protection, micrometeorite and stray ferrous object protection, to prevent plasma buildup and to keep Astronauts from coming too close to the magnet.

Astromag consists of a core facility (magnet, dewar, data system, etc.) plus a complement of ancillary detectors designed for specific scientific investigations. The core facility and ancillary detectors will be delivered by the STS to the Space Station and mounted on the outrigger approximately 10 meters from the main Space Station beam. Initial checkout and magnet charging and discharging operations will be performed once Astromag is installed on the Space Station. Astromag will be operated, under ground control, to collect scientific data. For such a facility, there are mechanical, electrical, thermal, data/command, and operational interfaces between Astromag and the Space Station. The current planning for these interfaces is discussed in this section. Safety issues are also discussed.

A. ASTROMAG CHARACTERISTICS

The initial configuration for the first generation experiments on Astromag is sketched schematically in Figure I-3 (page 5) and was described in preceding sections. Table V-1 summarizes the characteristics of Astromag with typical experiments on the Space Station. Mounting in an anti-Earth viewing orientation will be accomplished using STS and Space Station mechanical interface hardware to the extent possible. Ancillary detectors are mounted to the core facility using attachment points provided on the core facility. All detector systems should be modular and designed for easy removal for repair or reconfiguration for subsequent experiments.

Experiment operations are expected to require approximately 2 kw of power. The charged magnet will operate in persistent mode with the magnet current circulating perpetually in the superconducting coil. No power is consumed to maintain the magnetic field. For magnet charging, a total energy of 5 kwh will be consumed over a period of 10-12 hours. Magnet charging may be interrupted at various stages to conduct campaign-mode plasma physics studies in the Astromag fringe fields. A campaign might typically last a few days. Assuming on-board compression of data, it is estimated that a data downlink of 0.1 to 0.2 Mb/s will be required by experiments. A command uplink of 10 kb/s will be needed occasionally and can be shared with other experiments.

The mean operating temperature of the experiment detectors is assumed to be in the range 0-30°C. Detectors should survive over the range -10° to 40° C. Astromag will probably be designed to operate independently of the Space Station liquid cooling system. A passive internal thermal design will take

TABLE V-1

PRELIMINARY CHARACTERISTICS OF THE ASTROMAG FACILITY ON THE SPACE STATION

Size:	Cylinder, 4.5 m diameter, 4 m long (See Figure I-1)
Mass:	3000 kg (core facility) and TBD experiments
Operational Power:	2000 watts continuous
Magnet Startup Energy:	5 kilowatt-hours
Data Rate:	100-200 kilobits/second, continuous to ground
Orientation:	towards zenith, ± 45°
Aspect:	A posteriori knowledge, ± 2° rms
Field-of-view:	± 45° x ± 30° pyramidal
Orbital State Vector:	Require knowledge
Command Uplink:	10 kilobit/second, intermittent
Operating Temperature:	< 2 K for magnet, 0-30°C for instrumentation
Temperature Control:	SS cooling loop not required
Dewar Cryogen:	Superfluid He
LHe Vent Rate:	5 liters/day average
Mounting:	On outrigger attached to Space Station cross beam

waste heat from experiments to the core facility and from there it will be radiated to space. Of greatest concern is the temperature stability of the magnetic spectrometers. Small changes in temperature or the existence of temperature gradients may distort the magnetic spectrometers and affect their resolution. It is estimated that the spectrometers must be stable and uniform in temperature to ± 2°C in order to achieve the scientific objectives discussed above.

The particle astrophysics investigations require knowledge of the position of the instruments within the Earth's magnetic field when each particle event is observed. For this, accurate periodic updates of the experiment clock and knowledge of the orbital state vector as a function of time should be assumed to be available at the Astromag for merging with the experiment data stream. For particle experiments, post-facto attitude determination of ± 2° is adequate. More accurate knowledge of the attitude of Astromag needed (± 0.01° or better) for analysis of the gamma ray data would be provided by a star tracking system mounted to the experiment.

The electrical current flows through the two superconducting coils of Astromag in opposite directions so that the dipole magnetic moment is cancelled. There is, however, a substantial fringe field close to the magnet. This field falls off rapidly with distance. A map of the far field is given in Figure V-1 (Page 67). This fringe field could be used for a variety of other scientific investigations such as plasma physics experiments.

B. ASTROMAG OPERATIONS

Astromag is intended to operate as a facility and will therefore gradually evolve in its form. This section describes the STS and Space Station operations required to assemble, maintain, and reconfigure this facility. An overview of these operations is presented in Table V-2.

1. STS Operations

The magnet, dewar, and electronics constitute the core facility. The core facility will be carried to orbit in the STS bay as a single unit. In order to minimize the required cryogen, the magnet will be launched cold.

TABLE V-2

PARTICLE ASTROPHYSICS MAGNET FACILITY MISSION OPERATIONS SCENARIO

1. Ground testing of instrument and all mechanical, thermal, and electrical interfaces on Space Station simulators.

2. Fill the magnet with cryogen and transfer magnet, with the initial detector complement attached, to shuttle.

3. Convert the LHe into superfluid LHe and top off the LHe. a small vacuum pump will be operated in or near the cargo bay to maintain the LHe in the superfluid state until launch.

4. Launch. Within 2 minutes after launch, the ambient pressure within the cargo bay will be low enough to maintain the LHe in the superfluid state.

5. Reception by the Space Station.

6. Temporary storage (if necessary).

7. Construct Astromag outrigger.

8. Transfer Astromag to its outrigger, attach it.

9. Assemble instruments to the Astromag facility (if required). Construct (or open and then reclose) protective (thermal, micrometeorite, etc.) enclosure around Astromag.

10. Establish data, power, and command interconnects.

11. Activate Astromag thermal control system.

12. Establish ground control of instrument.

13. Test of data system, commands, by ground operations.

14. Activate and test experiments including trajectory devices and particle identifiers.

15. Take data to measure the alignment of the spectrometers (magnet off).

16. Charge magnet and conduct "campaign mode" plasma physics investigations.

17. Begin routine continuous operations under ground control.

18. Discharge the magnet to perform calibrations and servicing. This can be scheduled coincident with nearby EVA 3 or 4 times per year. Repeat steps 16-18.

19. Cryogen and counter gas resupply after 1.5 to 2 year--should be done before cryogen is exhausted. If cryogen is exhausted and magnet is allowed to warm up, it will require extra cryogen to re-cool the magnet.

20. Detector changeout on approximately 2-year intervals. Detector changeout will necessitate discharging the magnet. This involves looping through steps 9-17 above.

Therefore, cryogen must be added prior to launch. Once operating, the facility will require the STS for resupply of liquid helium (and other consumables) approximately every 2 years. In addition, at intervals of approximately 2 years, part or all of the instrumentation for the experiments will be replaced as the later stages of the observing program take place.

Note that if the resupply is delayed, and the magnet begins to warm, the facility would become inoperable and require extra LHe for cool down, but the facility would not be damaged. Operations could resume once the magnet was recooled and recharged.

2. On-Orbit Operations

Once the core facility has been transferred to its outrigger with the initial complement of experiments attached, connections will be made to the Space Station power, telemetry and data systems. Next, the experiments will be thoroughly tested, mainly under ground control. Data might be taken for a few days with the magnet off, in order to align the spectrometers. The magnet will then be charged, an operation that takes approximately 12 hours without interruption (see below). Once fully charged, the facility is ready to begin continuous data taking under ground control.

It is expected that approximately every 2 years the magnet will require resupply of LHe. It is also planned that at several month intervals the magnet will be discharged and then recharged in order to determine the alignment of the spectrometers. This can be done whenever the magnet is shut down as part of EVA activity taking place in the vicinity of the magnet. Campaign-mode plasma physics investigations could be conducted during these times with only minor impact on the particle spectrometer experiments.

Every 2 years or so the instrumentation of the facility will be changed out or reconfigured as the observing program of the facility evolves. It might be possible/necessary to temporarily store some of instrumentation on board the space station between the time it is installed/de-installed on Astromag and transported in the STS.

It is intended that the facility will take advantage of some of the unique capabilities of the Space Station such as servicing, on-orbit repair and storage without unduly taxing these capabilities.

3. Astromag Science Operations

An Astromag Science Operations Center (ASOC) will be established to provide planning, monitoring and initial data handling functions for the orbiting Astromag facility. It will be the contact between the Space Station Control Center and the Astromag scientists. Development of the SOC will be a part of the Astromag development task and will be a responsibility of the Facility Integration Science Team (FIST).

The ASOC will plan the experiment activities, generating command sequences required to configure the Astromag and conduct the observations. These sequences will be forwarded to the Space Station POCC for transmission to the Station. Returning data will include both housekeeping information to monitor the health and performance of the facility and science observations. The science data will be pre-processed, checked for quality, and distributed to the Investigators via network or other suitable means.

C. SAFETY

Superconducting magnets have been used in cosmic ray studies for over 15 years. A prototype of a magnet for use in space was constructed as part of the early HEAO program and is available for further testing. The magnet proposed for Astromag is larger than previously used in cosmic ray studies, but scaling to larger sizes is well understood from accelerator facility developments and is considered routine.

NASA has built liquid helium dewars on IRAS and COBE. The IRAS dewar performed as expected. A cryogen transfer demonstration (Shuttle Helium On-Orbit Transfer (SHOOT) experiment) is planned for the year 1990. These programs provide the background necessary for the operational and safety considerations.

Astromag will consist of a pair of magnets cooled by liquid helium in a dewar with complex systems of detectors to perform experiments in the magnetic field. The magnet will produce an extensive magnetic field near Astromag and will contain approximately 10 MJ of stored energy. The magnet cooling system will be designed to prevent the release of the magnet's stored energy directly into the LHe. In the unlikely event of a collapse of the field, the energy will go into heating the magnet coils. Recovery of the system would be accomplished by circulating vapor phase He through the coils to recool them prior to recharging the coils.

The most critical hazards from Astromag are electrical shock and explosion of the magnet dewar or gas storage containers. The detector systems will contain high voltage supplies and high pressure storage containers for the gas used in some of the detectors. There are also various hazards due to the effects of the magnetic field on ferrous materials. These hazards will be eliminated as described below:

In addition to the usual sources of electrical shock found in the electronic counters, care must be taken to insure that the magnet circuit is always closed. This hazard will be eliminated by design and fabrication techniques. The magnet will be designed to absorb the heat from a quench without warming above 100 K so as to avoid burning out the coil. This design will be verified in ground tests.

When fully charged, the magnet contains approximately 10 MJ of stored energy. The dewar will be designed to fail safely if other systems fail, and the pressure generated by a quench of the magnet dumps this energy into the dewar and the LHe as heat. The dewar will be designed and fabricated following NASA's pressure vessel standards. The dewar will contain multiple vent paths and blow-out disks to eliminate hazard of explosion. The safe operation of the dewar and magnet under extreme conditions of a quench will be verified by ground tests. In an emergency, the magnet can be quenched by command. The field will collapse in 1-3 seconds.

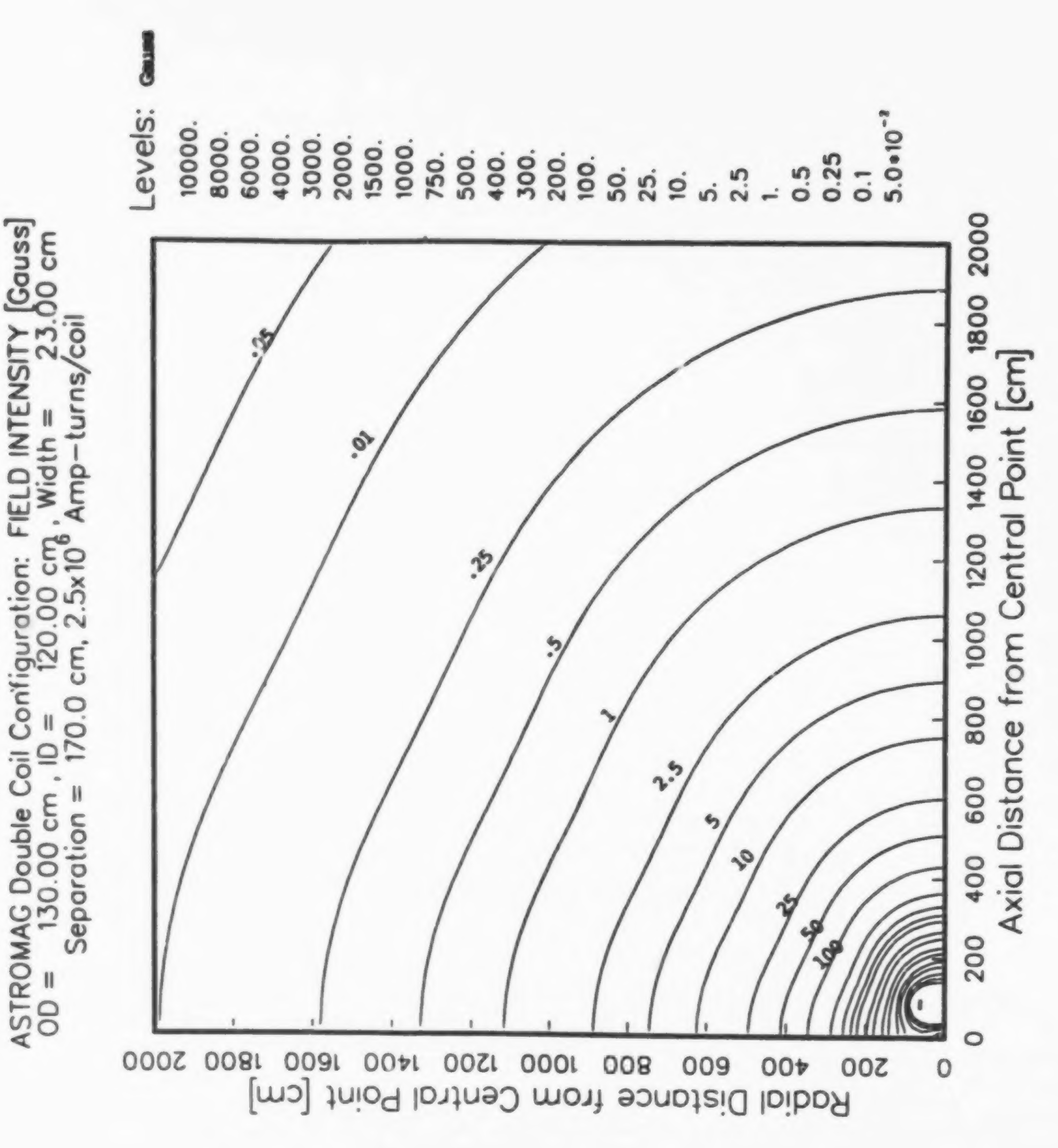

Figure V-2: Far field contour map for Astromag. The field equals the earth's field at a distance of 15 to 20 meters from the center of the magnet.

A map of Astromag's magnetic field, Figure V-2, shows that the field falls below 3 Gauss approximately 10 meters from the coil. Beyond 15 meters, the magnetic field is dominated by the Earth's field. There are two hazards from this field: it can cause mechanical devices like relays and solenoid valves to dysfunction and it can attract ferrous objects. The field region that could affect valves, relays, etc. is confined to the immediate vicinity of the magnet and will not affect other experiments or crew activities near other experiments. It has been assumed that safety requirements will dictate that the magnet be discharged for servicing or crew activities nearby. This can be done 3 or 4 times a year without seriously affecting the cryostat lifetime. The Astromag itself must be designed to intercept objects that are attracted to the magnet before they gain enough speed to be destructive. This will either be done by the external surface of Astromag or a specially constructed shield.

There are also safety issues associated with cryogenic re-supply. NASA is committed to develop this capability; SHOOT will be the initial demonstration of pumping superfluid LHe in zero g using a fountain effect pump. Cryogenic re-supply techniques should be well established before Astromag is flown.

The magnet will be charged and discharged/controlled from the ground but monitored closely by the crew. The software and hardware associated with these functions will be designed to prevent overcharging the magnet, charging at an excessive rate and other unplanned actions that might create a hazard. A charge/discharge cycle emergency override will be provided for the Astronauts.

The electronic counters will be designed to have all high voltage points insulated or otherwise protected from accidental contact. The gas pressure systems will be designed to NASA's pressure vessel standards.

By employing the design features and ground testing described above, we believe that all hazards associated with Astromag can be handled safely.

VI: MANAGEMENT PLAN FOR ASTROMAG

OVERVIEW

Goddard Space Flight Center, as the designated development Center, will manage the design, development, integration and qualification of the Astromag facility.

Figure VI-1 sketches the overall organization during development of the facility. Overall responsibility for the execution of the project rests with the GSFC Project Manager. The Project Manager works closely with the GSFC Project Scientist who is responsible for maximizing the science return from the mission within the project constraints. The Project Scientist is co-chairman of the Science Working Group (SWG) which is the primary science element of the project.

A Facility Integration Science Team (FIST), selected by NASA from among individuals who respond to an Announcement of Opportunity (AO), will provide technical support for the definition, development, and testing of the core facility, and will advise the project manager concerning procurement of the superconducting magnet and dewar, as well as central power, data, and structural systems,

The instrumentation for each experiment will be designed and developed by an experiment team selected from among teams which respond to the AO. For example, if the initial configuration of the facility were the "strawman" described in section IV of this report, there would be two experiment teams, one for the matter-antimatter spectrometer and one for the cosmic ray isotope spectrometer. Each team responding to the AO would be expected to propose a complete investigation, including all instrumentation except for the magnet and other central facilities described in the previous paragraph. While NASA will attempt to select teams in the form proposed, NASA will retain the right to select portions of proposed investigations. At appropriate times after the initial teams are selected, NASA would issue an AO and select additional teams for second-generation experiments. Some second-generation instruments may be selected for definition studies from the initial AO.

In addition to the FIST members and the experiment teams, NASA will select a number of General Investigators (GI). The GI's will include theoreticians and experimenters who have special knowledge and interest that would enhance the work of the experiment teams and/or the SWG. NASA will select GI's from among scientists who specifically propose for the position and from those who proposed as members of experiment teams which were not selected. NASA will assign GI's to work with experiment teams and/or to be members of the SWG.

During the mission-operations and data-analysis phase, the experiment teams will have primary responsibility for analysis of the data from their experiments. Members of the FIST will oversee the operations of the magnet and will become part of one of the experiment teams with responsibility to include, but not be limited to, oversight of interfaces to the core facility. Overall policy for the operation of the facility will be set by the SWG.

In the following sections we discuss each of the components of this organization in more detail.

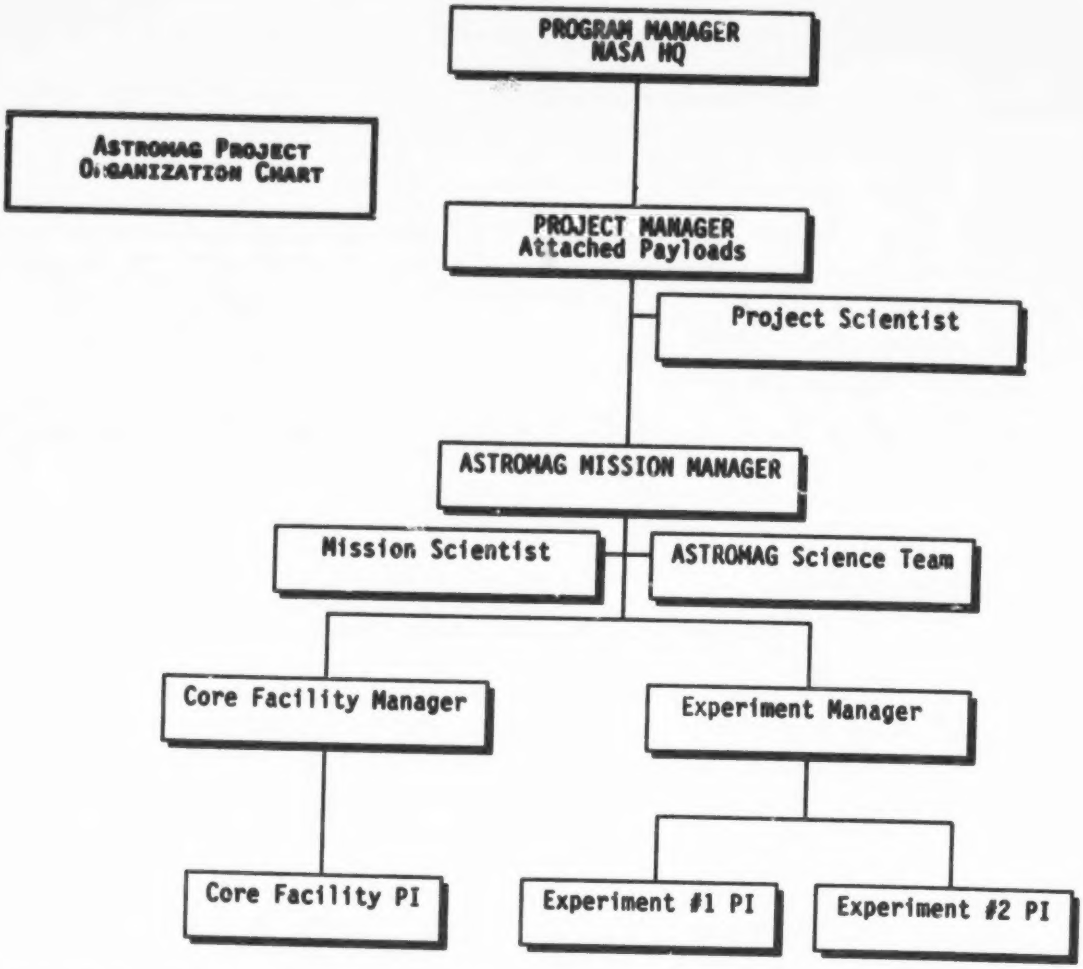
ASTROMAG PROJECT ORGANIZATION CHART
PROGRAM MANAGER NASA HQ
PROJECT MANAGER Attached Payloads
Project Scientist
ASTROMAG MISSION MANAGER
Mission Scientist
ASTROMAG Science Team
Core Facility Manager
Experiment Manager
Core Facility PI
Experiment #1 PI
Experiment #2 PI

Figure VI-1: Management organization for Astromag. The solid boxes indicate positions appointed by NASA officials. The dotted boxes are selected through the AO process.

SCIENCE WORKING GROUP

The SWG will be co-chaired by the GSFC Project Scientist and the SWG Chairman, a scientist from outside NASA, selected with the advice and consent of the members of the SWG. The Chairman and the Project Scientist will be jointly responsible for developing consensus among the SWG members. The Project Scientist will be the principal person in day-to-day contact with the Project Manager to assure that the consensus decisions are carried out.

Membership on the SWG will include the Principal Investigator and one other member of each of the experiment teams, the leader and one other member of the FIST, and approximately three General Investigators. Like the FIST members, these General Investigators will become attached to one of the experiment teams during the mission-operations and data-analysis phase.

During the design-development phase the SWG will set overall policy for the science program of the facility. The SWG will advise the Project Scientist, and through him the Project Manager, regarding tradeoffs in the experiment and facility design. During the mission-operations and data-analysis phase the SWG will set policy and make key decisions associated with operation of the facility and experiments in flight, but the experiment teams will act independently of each other in analyzing data and publishing results.

FACILITY DEVELOPMENT AND INTEGRATION SCIENCE TEAM

NASA has designated Goddard Space Flight Center (GSFC) as the lead center for development of Astromag. The GSFC will be responsible for the overall management of the project.

The core of the Astromag facility includes the superconducting magnet with associated dewar and its control and charging devices, the support structure, the central data system, power and telemetry subsystems, and all supporting equipment. The development of the core facility and experiments will be managed by the ASP (Attached Space Payloads) Project of the Flight Projects Directorate. The Engineering Directorate would have engineering responsibity for the development and deployment of the core Astromag facility. The Space and Earth Sciences Directorate would provide a Project Scientist and institutional science support. Other Goddard Directorates would support the development as needed. In addition to the facility hardware development, the project would provide equipment spares, ground support and servicing software. Contracts would be awarded as necessary to supply components, subsystems, engineering analysis, as required.

A Facility Integration Science Team (FIST) will be appointed by NASA from among individuals who apply. This team will have a leader appointed by NASA, and the Project Scientist will be an ex-officio member of the team. Members of this team will work closely with the project office in setting the specifications for the magnet and other facility hardware, in monitoring the contractors' development of these items, and in acceptance testing and calibration of the hardware. An extensive program of testing the magnet and of mapping its actual field configuration will be needed.

During mission operations and data analysis, members of the FIST will be responsible for close coordination with the GSFC mission operations team in supervision of all magnet operations, such as charging and resupplying liquid helium. During this phase, each member of the FIST will be attached to an experiment team and will participate fully with that team in data analysis and publications. As part of their original responses to the AO, Scientists applying for FIST membership will be expected to indicate with which Experiment Team (see below) they would ultimately like to become a part. Subsequent to selection of the FIST and the experiments, FIST members and experiment teams will be expected to reach agreement concerning their association.

EXPERIMENT TEAMS

Experiment teams will be selected in response to the AO. The AO will specify characteristics of the magnet which the experimenters can expect. Experiment teams will be expected to include, among the hardware they provide, the necessary track defining detectors. It is expected that these detectors may become part of the Facility, available for future facility experiments.

It is expected that proposals in response to this part of the AO will involve collaborations among scientists at various institutions, with fabrication being proposed either in-house, at industrial contractors, and/or in cooperation with GSFC personnel. Each proposal should involve a fully formed experiment team in which individual team members and institutions have well-defined responsibilities during the development phase, either having to do with hardware design and fabrication or with preparation for the mission-operations and data-analysis phase. However, proposers will be encouraged to identify work associated with the development which may be set aside for General Investigators. Each proposal will name a Principal Investigator who will have overall responsibility for the experiment.

Each experiment team will propose a complete set of detectors which will be capable, in conjunction with the magnet, of satisfying some of the principal scientific objectives of the facility. While proposers will be encouraged to be innovative in designing the system, they should recognize that the Astromag is envisioned as an evolving facility. The first experiments selected should be capable of achieving a few key objectives in a cost-constrained manner.

During the mission-operations and data-analysis phase, the experiment teams will operate essentially independently in data analysis. During this phase the teams will be expanded beyond their original size of the design-development phase to include members of the FIST and to include General Investigators who had been on the SWG. It is suggested that publications concerning the principal scientific objectives of each experiment will be co-authored by all the members of the expanded group. Publications resulting from secondary objectives suggested by subgroups or by guest investigators will not necessarily be authored by the entire group.

GENERAL INVESTIGATORS

General Investigators (GI) will be appointed by NASA to augment experiment teams in specific ways and/or to membership on the SWG. GI's will be selected from among people who specifically apply for the position in response to the AO, and from among individuals who were members of teams which responded to the AO but were not selected. GIs may be assigned to experiment teams or to the SWG because of theoretical experience important to the investigations, experimental experience, or because of other specific capabilities which would be valuable to the development of the facility.

FOREIGN PARTICIPATION

Participation by non-US scientists and institutions will be encouraged. There are several different ways in which they may participate. They may do so with their own experiment proposals with non-US principal investigator, or as members of a US-led group proposing to do an experiment. Foreign proposals for membership on the FIST and as General Investigator members of the SWG are also encouraged. It is also possible that foreign organizations may be selected to participate in development of the magnet or other central facility components.

RESILIANCY/STS ATTACHED OPERATIONS

Astromag is to be developed principally as a Space Station facility. The experiment teams will be selected accordingly. However, important but limited science could also carried out with the magnet in a high-inclination orbit during a one-week shuttle flight. If it appears that the magnet can be ready before the Space Station is available to accommodate it, then it might be flown first in a shuttle attached mode. To be prepared for this eventuality, experiment proposers might wish to consider those aspects of their instruments which can be accomplished by hardware which is integrated to the core portion of Astromag prior to launch. This also provides NASA with STS manifesting flexibility.

An STS launch of the Astromag and its first generation experiments is anticipated. However, since manifesting on the STS is subject to uncertainty, alternate launch options (e.g., DELTA) may be considered for the core facility. On orbit assembly of experiments is an option which experimenters might consider to increase NASA's flexibility in carrying these large experiments to the Space Station.

VII. TECHNICAL DEVELOPMENT PLAN

Although most of the technology for the Astromag facility and its initial experiments is well established, a sizeable engineering effort will be involved in the design and construction of the apparatus. In this section the major activities required for the development of the Astromag facility and associated first generation experiments are outlined. These activities are presented in the following general categories: magnet and dewar system, trajectory system, data system, and initial experiments. This effort will, with an optimal funding profile, extend over a period of eight years from the present pre-phase A definition effort to readiness for launch and integration onto the Space Station. Prompt initiation of these efforts will result in launch readiness by 1995.

For the experiments and the trajectory and data systems a 2 year Phase A (preliminary analysis) study which will result in a Request for Proposals for Phase B contractors and an Announcement of Opportunity for scientific investigations is anticipated. Phase B (definition) studies will occupy the next year and will provide the groundwork for a four year Phase C/D (design and development) effort. However, the system of superconducting magnet and associated dewar is the pacing long-lead item, affecting all areas of the facility and experiments. Therefore, an aggressive development effort aimed at firmly establishing the magnet and dewar system design in the first two to three years of the project is highly desirable. Adequate funding for this portion of the development will be necessary to fully specify the essential characteristics of the facility prior to the detailed design of the experiments. It will also assure adequate time in Phase C/D for the extensive integration and testing efforts required to complete the facility, mate it with the initial experiments, and thoroughly calibrate the complete apparatus. Figure VII-1 shows, in broad outline, the schedules anticipated for the various components of Astromag.

In addition, since the superconducting magnet system is to be operated as a facility with experiments being changed approximately every two years, work on second generation experiments should commence before the launch of the magnet. A plan for these efforts is presented.

SUPERCONDUCTING MAGNET AND DEWAR SYSTEM

The superconducting magnet and associated dewar and electrical system are the central features of the Astromag facility. Plans for the development of these items are based on the following assumptions: Three magnet coils will be constructed, and ground tests will be used to select the best coils for the flight magnet. The remaining coil will be used to construct a ground test facility. This ground system will be used for the preparation and calibration of experiments which will use the Astromag facility after the first generation. A total of three dewars will be needed: a test dewar suitable for testing individual coils of the magnet, a "flight dewar" for use in the facility, and a ground dewar similar in design to the flight dewar, but not qualified for space flight. The ground dewar will, after the testing phase, be the permanent housing for the non-flight magnet system. All three dewars will have outer vacuum shells to permit thorough testing on the ground.

Phase A (2 years)

Evaluate Options.

-Evaluate scientific and engineering trade-offs among candidate coil configurations and select magnet type.

-Investigate alternatives for magnet charging and operation (flux pump, retractable leads, gas-cooled or uncooled leads, persistent switches, secondary circuits for quench protection).

-Study alternatives for magnet cooling (helium pump, entirely passive cooling).

-Carry out preliminary studies of cryogen lifetime and magnetic stresses in candidate coil configurations.

Definition of Requirements.

-Establish requirements for data system support of magnet (e.g., control of charging, monitoring of magnetic field sensors).

- Design test magnet coil.

Phase B (1 year)

System Definition.

-Carry out preliminary design of magnet coils, dewar, power system, and cool-down system.

Engineering Model Studies.

-Build and test prototype magnet coil and charging system, including electrical leads and persistent superconducting switch.

Phase C/D (4 years)

Final Design.

-Finalize coil design and order superconductor and coil forms.

-Select dewar vendor and complete dewar design.

-Complete and review magnet system design.

Ground Support Equipment Development.

-Design ground dewar.

-Purchase liquid helium refrigerator for ground operations.

-Order test dewar and materials for ground dewar.

-Fabricate ground dewar.

Subsystem Fabrication and Test.

-Fabricate coils and characterize individual performance of each coil using test dewar.

-Select best coil set for flight magnet.

-Use ground test dewar for combined testing of coil sets in flight configuration.

-Construct basic parts for flight dewar.
Ground Magnet System Assembly and Test.

-Assemble integrated system of ground coils in ground test dewar.

-Test performance of ground magnet system.

-Map field of ground magnet.

Flight Magnet System Assembly and Test.

-Assemble integrated system of flight coils in flight dewar.

-Test performance of completed flight magnet/dewar assembly.

-Measure helium boil-off rate and determine lifetime of flight magnet system.

-Map magnetic field of flight magnet.

Integration with Experiments.

-Integrate experiments with ground magnet system and test.

-Integrate experiments with flight magnet and test.

Calibration.

-Perform calibrations and tests in accelerator beams with experiments mated to the magnet.

TRAJECTORY SYSTEM

Most of the Astromag objectives can be addressed using one of two basic detector configurations: one optimized for particles of low charge and the other for highly charged nuclei. As "strawman candidates" the study team assumed the former detector would be a multiwire proportional counter (MWPC) and the latter would be a scintillating optical fiber trajectory (SOFT) detector. Specific details of the definition studies that are underway or planned for optimizing these sensors to meeting Astromag experiment requirements. However, the technology for high resolution position sensing detectors is developing rapidly, and alternative approaches may prove advantageous. The technical development plan presented below is applicable for any of a variety of position sensing detectors that could ultimately be selected for the trajectory system.

Phase A (2 years)

Test-Model Studies.

-Construct engineering test-models of position sensing detectors and perform development studies to optimize sensor performance.

-Investigate readout electronics options and construct and evaluate breadboard prototypes.

-Investigate intrinsic resolution and dynamic range, and optimization of configurations for studies of low-charge and high-charge particles.

-Study systematic effects on resolution using large scale test model detectors and establish thermal control requirements.

-Study operation in strong magnetic fields.

Definition of Requirements.

-Study options for using flight data to calibrate spectrometer alignment and non-linearities using data from an existing balloon-borne magnetic spectrometer.

-Investigate packaging requirements and options (support frame minimization, pressure vessel, kinematic mounts).

-Define support system requirements (gas supply, alignment, calibration).

-Establish requirements for data system.

Phase B (1 year)

Technical Studies.

-Define mechanical requirements for sensor support and alignment.

-Perform thermal and mechanical studies of full trajectory system.

-Develop in-flight alignment and calibration procedures.

System Definition

-Carry out initial design of flight position sensors.

-Carry out initial design of thermal control system and gas system.

-Do initial design of ground and flight calibration systems.

Phase C/D (4 years)

Final Design.

-Finalize design of trajectory systems.

-Design fixtures for construction and testing of flight trajectory systems.

-Finalize ground and flight calibration system designs.

Fabrication.

-Fabricate flight sensors, mechanical supports, thermal system, and gas system.

-Construct ground and flight calibration systems.

Integration.

-Integrate trajectory systems with experiments.

-Integrate experiment apparatus (including trajectory systems) with magnet system and test.

-Deliver experiments for integration with Space Shuttle/Space Station.

Test and Calibration.

-Carry out preliminary tests of flight trajectory system.

-Calibrate and map trajectory system.

-Perform system calibrations, including tests with accelerator particle beams.

DATA SYSTEM

The Astromag data system interacts with the core facility, with the experiments and with the Space Shuttle and Space Station. For the core facility it provides the monitoring and control functions for the operation of the magnet and dewar. For the experiments it provides limited onboard processing, calibration functions, and a uniform interface to the Space Station. And for the Space Shuttle and Space Station it is the single point of contact for the passing of commands, and of housekeeping and experimental data. Thus the specific requirements for the data system will evolve as the definitions of the core facility, the experiments, and the Space Station interfaces develop. An essential aspect of the data system definition will be the identification of an architecture which will meet the needs not only of first generation experiments, but also of subsequent experiments which are not yet well defined.

Phase A (2 years)

Identify Requirements.

-Collect data system requirements imposed by Space Shuttle/Space Station, magnet, and experiments (including second and later generations).

Studies of Architecture Options.

-Identify candidate architectures.

-Compare candidate architectures against requirements and identify tradeoffs.

Phase B (1 year)

Technical Studies.

-Develop and test prototypes of critical hardware and software elements.

Preliminary Hardware/Software Design.

-Select architecture of flight data system hardware and software.

Phase C/D (4 years)

Final Hardware/Software Design.

-Final design of flight data system hardware and software.

Fabrication.

-Fabricate data system.

Integration.

-Integration and checkout of interaction with Space Shuttle/Space Station, magnet, and experiments.

System Tests.

-Support accelerator calibrations of experiments.

-Support integration and testing of the facility and experiments on the Space Shuttle and on a Space Station interface simulator.

INITIAL EXPERIMENTS

The initial Astromag experiments will require the development of a variety of detectors. For example, the straw-man experiments described in Section IV would require Cherenkov counters, transition radiation detectors, ionization detectors of various types, and electromagnetic shower detectors. While devices of all of these types have been used in balloon and space experiments, Astromag will require detectors having both larger area (2 m^2) and higher resolution than those flown in the past.

A significant fraction of the initial sensor development needed for Astromag experiments are expected to have been carried out under the Supporting Research and Technology (SR/T) program. These efforts will involve laboratory prototyping and accelerator tests. In addition, balloon-borne experiments will allow versions of the various sensors to be integrated in appropriate combinations, and then tested in an environment similar to that encountered in space. Thus it will be possible to investigate resolution, stability, dynamic range, and sources of background in time for appropriate modifications to be made before the design and construction of Astromag experiments.

The detailed items in the following schedule are illustrative of the developments needed for possible initial Astromag experiments such as those discussed in Section IV. This represents only a fraction of the detector development work underway in particle astrophysics, and the specific sensor systems for initial Astromag experiments, which will be selected through the AO process, may well involve detectors not discussed here.

Phase A (2 years)

Test-Model Studies.

-Optimize sensors, including Cherenkov counters ($n<1.1$), transition radiation detectors, time of flight detectors, and position sensitive shower counters.

-Optimize magnetic shielding techniques for photomultiplier tubes.

-Develop detector calibration methods.

Balloon-Borne Detector Operations.

-Test sensors in various combinations in a space-like environment to investigate resolution, stability, dynamic range, backgrounds, etc.

-Carry out balloon flights of a small magnet and prototype sensors.

-Test particle identification and mass resolution techniques.

Phase B (1 year)

Technical Studies.

-Optimize sensor parameters for specific requirements of experiments.

-Perform accelerator tests of planned detectors.

- Fabricate and test "bench model" detector.

System Definition.

-Carry out initial design of flight detector systems.

-Evaluate mutual requirements of trajectory system and the remainder of the experiment, including electronic interfaces.

-Do initial design of ground support system.

Phase C/D (4 years)

Final Design

-Finalize experiment designs.

-Design support systems (gas resupply, thermal control, calibration monitoring, etc.)

-Design interfaces to the facility.

Fabrication.

-Construct flight sensor system, electronics, and support systems.

-Fabricate ground support equipment.

Integration.

-Integrate trajectory system with the remainder of the experiment.

-Test experiment integration using ground magnet.

-Integrate experiments with flight magnet.

Test and Calibration.

-Perform functional tests of completed experiments.

-Carry out accelerator calibrations and experiments (e^+, e^-, p, $\overline{p}$ at Fermilab, SLAC; isotopes at Brookhaven.)

FOLLOW-ON EXPERIMENTS

Following the initial experiments, the Astromag facility will be reconfigured for other investigations. Among the important objectives that are envisioned are studies of light isotopes at energies in excess of 10 GeV/amu, advanced anti-nuclei searches with significantly improved discrimination power, studies of electrons at energies above 1 TeV, sensitive measurements of high energy gamma ray line and continuum radiations, and searches for exotic particles in the cosmic radiation. The detectors needed to address most of these objectives are technologically more advanced than either present devices or detectors envisioned for first generation experiments.

For example, while the particle fluxes and the magnet spectrometer resolution are sufficient for studying light isotopes to above 50 GeV/amu, present Cherenkov counter techniques can provide adequate velocity measurements only up to about 10 GeV/amu. Promising devices for accurate energy determinations at higher energies include ring-imaging Cherenkov counters which have been used successfully at accelerators. In order to achieve the performance required for Astromag experiments, studies will be needed to optimize the designs for high resolution, to determine the response to particles at a variety of angles of incidence, and to develop space qualified versions of these detectors.

For studies of high energy gamma rays and possibly of trans-TeV electrons it will be necessary to determine the energies and directions of photons through measurements of the e^+, e^- pairs that they produce in target material above the magnet. This requires multi-track capability in the trajectory system and a segmented electromagnetic shower counter below the magnet to measure individual secondary particle energies. Such devices have been built on a small scale, but it remains to develop such a counter for a large area space experiment while maintaining both fine position segmentation and good energy resolution.

Long-range developments of these and other advanced technologies will proceed under the SR/T program. Preliminary selection of some second generation Astromag experiments should occur at the same time as the initial experiments are selected for flight. This selection will be followed, for second generation experiments by more extensive study phases before developing the experiments for flight. This experiment will provide new instruments for the first change out of experiments after about two years of operation.

SCHEDULE

Table VII-1 shows the funding estimates from cost modeling studies. The costs are consistent with the project schedule. Costing is based upon the GSFC in-house system development and project management, supported by industrial contracts and a Facility Integration Science Team (FIST). It is based upon the schedule shown in Figure VII-1.

Programmatic plans should be developed according to the Schedule shown in Figure VII-1.

ASTROMAG SCHEDULE

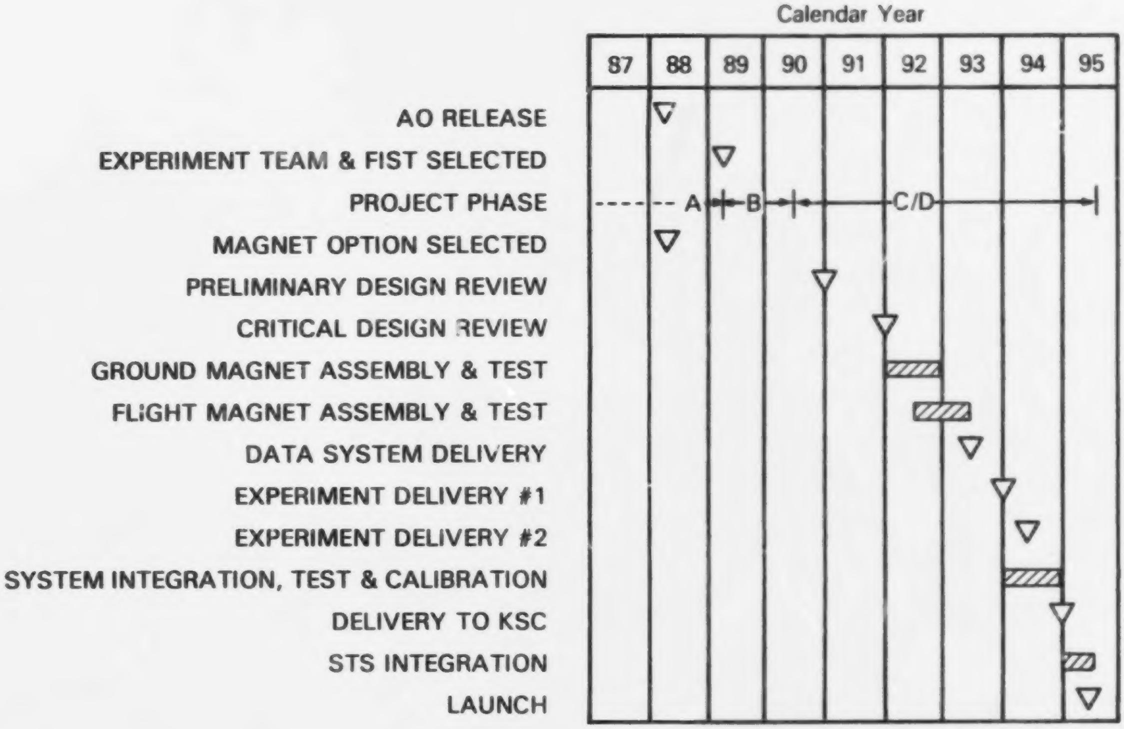

Figure VII-1: Astromag Schedule